Optimizing the Cost Efficiency of Wind Power Plant Projects

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ABSTRACT OF THE
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This thesis studied the cost optimization of wind power plant projects through both a literary study as well as computer software simulations and modelling, in order to both find the most crucial components in a wind power plant project. That knowledge was then directly applied in preparing future bids for the upcoming wind energy auction in Finland. The components identified as the most crucial in terms of the cost optimization of wind power plants were power purchase agreement size and duration, the production of the turbines, pricing forecasts, total losses, turbine and service costs, grid connection, weight and foundation, balance costs, land rent and debt interest among other, less significant, factors. The bid was then optimized based on the previous information.

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Tämä diplomityö tutki tuulivoimaloiden ja tuulivoimaprojektien kustannustehokkuuden optimointia sekä kirjallisuus- että tietokoneohjelmistotutkimuksen avulla. Työn tarkoituksena oli tunnistaa kriittisimmät komponentit tuulivoimaprojektien kustannuksissa, jonka jälkeen tuota tietoa käytettiin suoraan tulevaan Suomessa järjestettävään tuulivoimahuutokauppaan valmistautumisessa. Työn tunnistamiin kriittisimpiin komponentteihin tuulivoimalaprojektien osalta kuuluivat niin ennustukset sähkön hinnasta, sähkönhankintasopimuksen suuruus ja kesto, tuulimyllyjen tuotanto, tuulimyllyjen häviöt, tuulimyllyn hinnan ja huollon kustannukset, verkkoon liittyminen, paino ja perustukset, verkon säätökustannukset, maan vuokraus, velan korko sekä muita, vähemmän merkittäviä kustannuksia. Tämän jälkeen tarjoushuuto tulevan huutokaupan osalta optimoitiin edellisen tiedon pohjalta.

Avainsanat: Energia, Pääoman tuottoaste, Syöttötariffi, Tehokäyrä, Tuuliturbiini, Kapasiteettikerroin, Sähkön hinta, Tasattu energiantuotantohinta, Yritysarvo, Liikearvo

Preface

I want to thank European Energy for giving me a chance to write my thesis about a topic I am passionate about. I want to thank Martin Graa Jennum for helping me out when I had painted myself in a corner with the Excel, and I want to thank Gustaf Ekberg for his excellent input and guidance as my instructor, as well as Matti Lehtonen for his supervision of the thesis.

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Contents

Abstract **ii**

Abstract (in Finnish) **iii**

Preface **iv**

Contents **v**

Symbols and abbreviations **vi**

1 Introduction **1**

2 Wind Power Plants and Their Economic Structure **4**
2.1 The Cost of Energy for Wind Power Plants 5
2.1.1 Grid Congestion and Adding Wind Power to the Grid 13
2.2 Stages in Wind Power Plant Development 15
2.3 Wind Power and the Cost of Wind Power in the Future 15

3 Research Material and Methods **19**
3.1 Material 19
3.2 Methods 19
3.2.1 WindPRO 20
3.2.2 Microsoft Excel 23

4 The Cost Structure Optimization of Wind Power Plant Projects **30**
4.1 The Costs of Wind Power Projects 35
4.1.1 Offers from Wind Turbine Manufacturers 36
4.1.2 Foundation, Grid Connection, Logistics and Road Costs . . . 40
4.2 WindPRO Data 41
4.3 Excel Analysis 45
4.3.1 Identifying the Crucial Parts for the Auction Bid 45
4.3.2 Optimizing the Crucial Parts for the Auction Bid 50

5 Results **58**
5.1 Analysis of the Results 58
5.1.1 Components to Optimize When Looking at the Cost of Energy of Wind Power Projects 58
5.1.2 Recommendations for the Auction Bid Based on the Data and the Initial Proposal 59

6 Summary **63**
6.1 Recapitulation 63
6.2 Conclusions 66

References **69**

Symbols and abbreviations

Symbols

A	Area
CO_2	Carbon dioxide
C_{t}	Cash Flow
C_0	Investment costs
h	Height
n_{Gw}	Goodwill
n_{RoE}	Return on Equity
P	Power
r	Interest
v	(wind) Speed
W	Watt
z_0	Roughness length
€	Euro

Operators

$\log()$	Logarithm
$\ln()$	Natural logarithm
$\sum_i$	Sum over index i

Abbreviations

AEP	Annual Energy Production
CAPEX	Capital Expenditures
CF	Capacity Factor
COE	Cost of Energy
EV	Enterprise Value
FiP	Feed-in Premium
FiT	Feed-in Tariff
GoO	Guarantee of Origin
Gw	Goodwill
GWEC	Global Wind Energy Council
IEA	International Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
LEC	Levy Exemption Certificate
MWh	Megawatt hour
NPV	Net Present Value
OPEX	Operational Expenditures
PCC	Point of Common Coupling
PPA	Power Purchase Agreement
RoE	Return on Equity
SODAR	Sound Detection and Ranging
WPP	Wind Power Plant
WTG	Wind Turbine Generator

1 Introduction

Faced with the possibly of catastrophic effects brought forth by anthropogenic global warming, the world desperately needs to change the way that we produce energy in order to power our daily lives. Scientists are in agreement that in order to minimize the effects of said man-made global warming, the temperature increase induced by climate change should be kept to a minimum of 2° C. The Climate Action Roadmap by the European Union suggests that member states reduce their greenhouse gas emissions, especially carbon dioxide (CO_2) by 80 % below 1990 levels, a target to which all sectors need to contribute to [1]. Similar action needs to be taken all around the world, and international agreements such as the Paris Agreement in 2016 have aspired to give a framework for countries to do just that. The Paris accord, a voluntary pledge for countries to reduce their greenhouse gas emissions and move towards a more sustainable energy future, entered into force on the 4th of November 2016, after 55 parties, accounting for more than 55 % of global greenhouse gas emissions, had ratified it. As of June 2017, 148 out of 197 countries had ratified the Paris agreement [2]. (Although it should be noted that The United States recently announced that it would be pulling out of the agreement.) In order to achieve the targets set by the agreement and other emission cuts, the world needs to rethink its strategy and approach to producing energy.

According to an estimate by the International Energy Agency, global energy consumption is going to increase by up to 37 % from 2012 to 2040 [3]. As the world struggles to rid itself of environmentally catastrophic fossil fuels and their consumption, wind power is one of the options we look to now to make us less dependent on carbon-intensive ways of producing energy. Wind power plants require no fuel to burn and therefore can be utilized in order to move to less polluting ways of producing energy. Wind power is a rapidly growing and developing share of the energy market in Europe and all over the world. During the year 2014, wind turbine prices decreased around 3-5 %, and onshore wind accounted for over a third of the renewable capacity and generation increase in 2015 [4]. In the year 2016 alone, more than 54 Gigawatts of this clean, renewable energy resource was installed around the world, and in more than 90 countries. The global amount of installed wind power capacity will soon surpass 500 GW, and, by the looks of it, is going to continue to improve. According to the Global Wind Energy Council (GWEC), around 16 % of the global energy demand in 2020 could come from wind power [5], and by 2021, GWEC predicts that there will be over 800 GW of installed wind power capacity around the world [6].

But environmental issues are not the only upside of wind power. It also has significant economic advantages, including the cost of producing energy, as well as making society less dependent on fossil fuel prices, which can be very volatile [7]. It is this volatilty that has once again proved that necessity is the mother of invention. Countries all around the world have tried, some with more success than others, to distance themselves and their economy of this uncertain and unpredictable fuel that drives economies all around the world. Wind power has come a long way in the past few years and decades. The decreased prices mean that countries that are at the forefront of wind energy such as Denmark, are now reaping the benefits. After installing the first, 30 kilowatt (kW), modern wind turbine in 1979, Denmark has since made significant advancements in the field. Denmark now covers more than 40 % of its energy needs with wind power, and aims to produce over 50 % in 2020 [8].

It is important to determine the main factors in the cost of wind power plants, as these can then be utilized both in terms of governmental support schemes for green energy, but they can be utilized by companies as well trying to figure out the most economically viable way of financing a project, and whether a project is viable at all. Companies or investors investing in wind energy may also need to get used to a different monetary structure than with conventional energy projects, since wind power plants require no fuel and once operational, can start producing electricity without any additional requirements. Although wind power plants are more of a long-term investment, wind power can be seen as a very attractive investment for a company both looking to add green energy and green values to their portfolio, but also to make a profit, provided that the company does not need a more immediate return on their capital.

While wind energy has taken significant strides forward in the past few decades, it still has ways to go. Many issues around wind energy could still be vastly improved, especially in terms of its cost structure. The aim of this Master's thesis was was to optimize the cost efficiency of wind power plant projects, which is to say to optimize the cost as well as the profit of wind power plants being built around the world. There are many moving parts in the cost structure of a wind power plant project, including not only the cost of the actual rotor, but also externalities such as the cost of substations, transformers and grid connections. Wind power plants these days are rarely located in populated or easily-accessible areas, meaning that, while problems with noise become less significant, new costs might arise such as the cost of a good foundation for the heavy machinery as well as roads that support them.

Due to the many different aspects that come together to make the complete cost structure of a wind power plant, it is sometimes challenging to have a step-by-step instruction on what to do in terms of optimizing the cost structure of wind power plants due to their changing nature. This Master's thesis aims to put at least some of those challenges to rest, and make a few simple guidelines and steps to follow in every wind power project, regardless of their differences and instead focuses on what all projects have in common in order to both minimize costs as well as maximize proficts in order to make the project as attractive as possible to an investor.

The profits that wind power generate depend not only on the costs, but also the amount of energy produced, and therefore, naturally, the price at which that energy is sold: the market price of electricity. The amount of energy produced similarly depends on many different things, including the air density as well as the wind speed at the location of the wind turbine generator (WTG). Naturally, the price of energy as well as different government subsidization policies such as feed-in tariffs (FiTs, a guaranteed minimum price for energy or electricity produced in a certain manner) or a carbon tax scheme (a system where governments impose taxes on emissions, encouraging companies to reduce their emission levels in order to maximize profit) can also have a significant impact on the profit that a wind power plant can generate.

The aim of this Master's thesis was to take into account as many aspects of the economic structure of a wind power plant as possible, identify which ones can be altered or tinkered with to make a more optimal design, as well as to determine which parts should be altered in order to reach the optimal cost structure of a wind power plant. The work was done for a Danish company, European Energy, for them to use in actual wind power plant planning in preparing for an upcoming auction and to make a bid for some wind power plant projects in Finland. European Energy is an international company that builds, develops and finances wind and solar farms. European Energy operates in 11 different countries, with an installed capacity of 789 MW [9]. The data used was actual data and figures from wind turbines and wind power plant projects. The master's thesis and the data was used to plan four wind power plant projects in Finland in preparation for the auction, to be situated in Ahvenneva, Honkakangas, Mustalamminmäki and Koiramäki: a total of 24 turbines, with Mustalamminmäki representing all the sites. The main question was to look at whether wind power plants could be cost optimized further, and if so, how that could be achieved: in terms of reducing costs, improving production as well as making the best possible financial structure in order to make an attractive a bid as possible. This was done in many phases, starting from getting offers from actual wind turbine manufacturers (denoted here only by Manufacturer A, Manufacturer B, Manufacturer C and Manufacturer D due to non-disclosure agreements signed by European Energy), looking at the respective offers' prices as well as production and other factors affecting the cost and the profit and then determining the most cost effective solution. The focus of this master's thesis was on the design choices that can be made in the construction phase or prior to that phase, and some things such as the cost of different materials or replacing materials with other, cheaper alternatives was not studied. It may also be important to note that this Master's thesis focuses on onshore wind power plants, and does not delve too deeply into offshore wind projects, although they are mentioned occasionally as an interesting tidbit. Onshore wind power plants and projects have a lot of variation as it stands, and adding offshore to that mix is beyond the scope of this Master's thesis.

The first thing this Master's thesis focuses on is the basics of wind power in general, as well as the basic economic components of a wind power plant's cost structure, and how the different components come together to make the cost structure of a wind power plant. Then the study moves on to briefly discuss previous suggestions on how the performance of wind power plants and their cost structure could be improved, by looking at things such as Return on Equity (ROE), which should be a good indicator as to whether it is profitable to invest in a specific wind power project. When using Return on equity, the amount of loan in the total investment is an important factor, which was also optimized. After that, the thesis moves on to present the research material and methods used in the study (or the project), before moving into presenting the offers from the manufacturers as well as the actual cost structure optimization of wind power plants with the methods previously laid out and therefore presenting the bid for the auctions, followed by a brief analysis of the results as well as a summary.

2 Wind Power Plants and Their Economic Structure

As mentioned before, a big economic benefit of wind power (as well as various other forms of renewable energy sources) is that it decreases the dependency on the volatile price of fossil fuels. This economic impact could even be seen as great enough to justify a higher price (€/kWh) than with said fossil fuels. The markets may have a hard time solving this problem on their own, since the calculation methods used currently do not adequately take risks into account. Nor do they take into account the societal benefits of independence of fossil fuel pricess. The markets need to be assisted by governments to include all the costs arising from various forms of energy production, including what is currently considered costs for others and not the power companies, such as dumping waste. In addition, policy options that governments have include FiTs, carbon taxes or carbon trading green certificates of renewable energy credits. [7]

The production P of a wind power plant depends mainly on three important characteristics of wind power: the amount of air, referring to the volume, the speed of air, referring to the velocity, and the mass of air, which, combined with the volume, gives the density of the air.

The equation for the production can be acquired from some basic equations in physics:

$$E = \frac{1}{2}mv^2$$

And density can be acquired from

$$\rho = \frac{m}{V}$$

While the volume V can be solved as Av, combining the equations gives the basic formula for the power production of a wind power plant:

$$P = \frac{1}{2}\rho_{air}A_r v_{wind}^3 \tag{2.1}$$

Where ρ_{air} refers to the density of air, A_r refers to the area that the rotors of the wind turbine cover, and, importantly, v_{wind}^3 refers to the velocity of air. In other words, the maximum amount of energy available for a wind turbine to convert into electricity is mainly dependent on the cube of air speed [10], as well as somewhat dependent on the density of air and the area that the turbine sweeps. Sometimes mechanical efficiency C_p is also added to the end of Equation 2.1. Often constructing a larger wind power plant (one with a higher hub height) means that wind speeds are higher, but consequently air density also goes down somewhat. Wind turbines that produce most of their electricity at low speeds are called *system-friendly*. Equation (2.1) does show, however, that wind speed is a much larger fraction of the overall produced power than air density, and a small negative change in air density does not trump a small positive change in air speed. In order to calculate wind speeds at specific heights, the following equation is often used [11]:

$$v_{h1} = v_{h2} \cdot \frac{ln\frac{h_1}{z_0}}{ln\frac{h_2}{z_0}} \tag{2.2}$$

Where v_{h1} is the wind speed at height h_1 when wind speed at height h_2 is known. z_0 is known as a roughness length, which refers to a unit that takes into account the infrastructural elements, such as whether there are a lot of trees, buildings or other obstacles nearby. Generally, z_0 can be estimated as being one-tenth of the height of obstacles below. [12]

Generally, wind speed can be modeled by a Weibull probability distribution, which in this master's thesis is done by utilizing the WindPRO software. The Weibull distribution equation in its general form can be given as presented below in Equation 2.3. [13]

$$f(x) \;=\; \frac{k}{\lambda}(\frac{x}{\lambda})^{k-1}e^{-(\frac{x}{\lambda})^k}, \qquad x \geq 0 \qquad [13] \tag{2.3}$$

Where λ represents the scale parameter and k is used to denote the shape parameter, both important factors when determining the probability distributions of wind. The Weibull distribution for the projects under examination here are presented in Chapter 3. [13],[14]

2.1 The Cost of Energy for Wind Power Plants

The cost of different onshore wind power plants is often quite similar, although the investment costs might be a bit higher for offshore wind power plants, which they make up with more production as the wind speeds are often higher. (It should maybe be noted that here and throughout this master's thesis the type of wind turbine is a traditional horizontal axis turbine, instead of other designs such as vertical axis turbines.) As a rule of thumb a majority, about 50 - 80 %, of the total costs of a (new plant, old repowered turbines might have a different cost structure due to the need of maintenance) wind power plant come from the actual plant, including things such as the cost of the turbine, grid connection and electrical equipment. Constructing a bigger turbine means more weight, which is one of the main factors that increase the costs of a wind power plant. [14]. This makes wind power plants capital intensive (and therefore more suitable for long-term investments) when compared to other, more traditional, fossil fuel power plants, where operations & management (O&M) can account for anywhere between 40 to 70 % of the costs (For onshore wind energy, O&M costs are around 1 to 1.5 c€/kWh over the lifetime of the turbine). Costs that include O&M costs, capital costs as well as fuel costs, are often called the Levelized cost of energy (LCOE). LCOE is a tool used to evaluate the Costs of Energy of different projects, and compare them. For this project, Cost of Energy, COE, is used, which is usually the factor being referred to while discussing the cost structure optimization of wind power plants in this thesis. A more detailed description of the cost structure of wind power plants can be seen in Figure 2.1 below [7].

	INVESTMENT (€1,000/MW)	SHARE OF TOTAL COST %
Turbine (ex works)	928	75.6
Grid connection	109	8.9
Foundation	80	6.5
Land rent	48	3.9
Electric installation	18	1.5
Consultancy	15	1.2
Financial costs	15	1.2
Road construction	11	0.9
Control systems	4	0.3
TOTAL	1,227	100

Figure 2.1: The cost structure of a 2 MW wind power plant [7]

The total costs of wind power generation can generally be divided into three sections: direct, indirect and externality costs. O&M costs mentioned earlier, as well as capital costs are a part of direct costs and include things such as the turbines and other equipment, construction costs, road costs, costs of purchasing or leasing the site and constructing the transmission lines that connect the wind power plant to the grid. Indirect costs, on the other hand, have to do with connecting wind power to the grid, and are dependent on other forms of electricity generation in the area, the system load profile, ways of storing electricity, as well as the markets and connectivity to the grid in the area in general. These changing factors make indirect costs somewhat difficult to predict at first hand, and are very dependent on the location of the power plant. (Even the O&M costs mentioned before can vary greatly in quantity depending on the location of the power plant [15]) This is also reflected in the LCOE of wind power, as the LCOE can vary from anywhere between 3 c€/kWh to 10 c€/kWh. Due to this, it is often difficult to compare different projects, even if LCOE, a tool specifically designed to take many different things into account, is used. [16]. External, or externality, costs arise from other effects of wind power generation. They include noise pollution, impacts on wildlife, visual factors and other effects such as possible adverse health effects, which are very dependent on location. [17]

A more comprehensive picture of the total costs surrounding the construction and maintenance of a wind power plant can be seen in Figure 2.2, where more than just the installation of the turbine and the turbine itself are taken into account. Figure 2.2 shows the amount of moving parts in the operation and financing of a wind power plant and gives a brief overview of the amount of parts that can be optimized in terms of their cost to produce the best and most profitable outcome.

Naturally, the cost of the turbine, which in the above example covers around 75 % of the total cost of the wind power plant itself, can also be broken into smaller

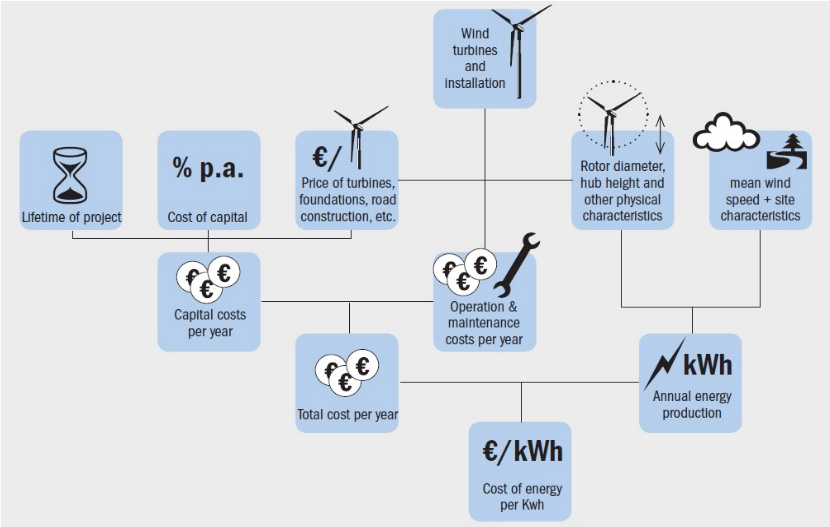


Figure 2.2: The cost structure of a wind energy plant [18]

components, depicted here in Figure 2.3 below. The cost of the materials used to make the different components is beyond the scope of this thesis, but Figures 2.1 and 2.3 should give some idea of how large of a part the cost of component materials really is, and whether it can be changed all too significantly. There are also other costs that wind power plants have, some of which have been previously mentioned. The site needs to be accessible by a proper road to haul in the heavy machinery, and the equipment also needs to be maintained and repaired every now and then.

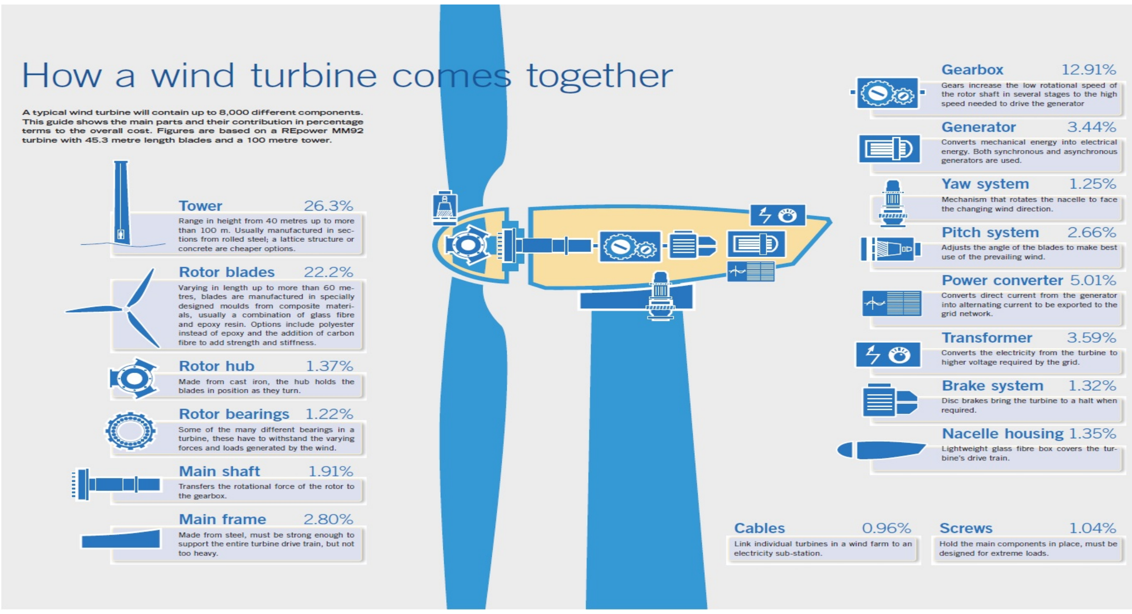


Figure 2.3: The cost of different components in a wind turbine and their share of the overall cost [19]

The output of a wind power plant (WPP), and therefore a big part of the profit production of a wind power plant, can be seen to depend largely on three technology characteristics: hub height (the turbine without the rotors), generator nominal power as well as rotor blade length. As mentioned before, wind speed at the designed height is also an important factor. Naturally, electricity and energy price is also an important factor when determining the profits generated by a wind turbine, to be talked in more detail later. A higher turbine does cost more due to the fact that more materials are used, but the increase in wind strength (wind speed) often results in a greater electricity production, which often makes the additonal investment worth it. A longer rotor blade, on the other hand, means that more wind is gathered through the larger area that is swept by the rotor. If the nominal power of a generator is low, it implies that the optimal conversion level is lower and already obtained at lower wind velocities. These are used in the power curve of a wind power plant, which indicates how much energy a wind power plant can produce under different circumstances. An example of a wind power curve can be seen in Figure 2.4. Figure 2.4 includes both a system-friendly approach as well as a system-unfriendly approach, and it illustrates the differences between the two approaches, and their respective strengths. Due to this, modern turbines often have several generators, working at different wind speeds, hence why their performance specification is often denoted as (Power of) Generator 1/ Generator 2 [14]. It could be said, as a rule of thumb, that the system-friendly turbine is the safe and easy approach, while the system-unfriendly approach is more ambitious and more of a high-risk high-reward type of approach.

The *specific power*, measured in W/m^2 of a wind power plant, tells how often a wind power turbine is able capture enough energy to power its generator at nominal power. Low specific power equals long rotor blades and a low nominal power, leading to a high capacity factor (CF), which refers to the equivalent of full-load production hours of a power plant in a year: the capacity factor of a good power plant typically exceeds 0.3 or 30 %. In other words, a capacity factor of 30 % for a wind turbine refers to the fact that 30 % of all hours in a year (8760 hours, so this equals a little over 2600 h) are full production hours. This means that a high capacity factor is not always a positive thing: a high capacity factor might mean that, while the site does produce at its rated power a more significant amount of time, the site might be able to produce more energy with a turbine of a higher rated power, but a lower capacity factor. This tradeoff is often quite case specific, though, and therefore increasing the capacity factor is often interchangeably used as an equivalent of increasing the overall production of a wind turbine.

By simply using the CF and the wind yield, as well as the rated power of a certain wind turbine, the yield (in Wh) can be calculated. This was done in order to assess the different productions of the different wind turbines, while also taking the losses into account. Once an assessment of the production is acquired, a rough estimate of the revenue of the wind power plant can be calculated, by simply applying a few key factors: the possible feed-in tariff price (if one exists), as well as the current market price of electricity. As briefly explained before, a tariff is a guaranteed price to be paid for electricity generated in a certain manner, used by for instance governments in order to encourage energy production in other, possibly unconventional, ways and ensure a broader energy mix. Because the projects looked at in this master's thesis are located in Finland, the Finnish FiT or purchase agreement price is the price being looked at. If the tariff is set too high (as many argue happened with Matti Vanhanen's government in Finland in 2010, when the premium/tariff price for electricity produced by wind power was set at 83.5 €/MWh, and market price of electricity at that time was around 57 €/MWh [20], [21]: a premium is similar to a tariff, but instead of a fixed price the premium is dependent on the market price, and its paid on top of the market price; in this thesis, tariff and premium were both used in order to represent an external support scheme) there might be almost too much of an incentive for companies to build wind power generation, leading to a lot of players entering the market in hopes of an easy profit, and the difference between the tariff price and the market price is paid by the customer. If the tariff price is set too low, however, there might not be enough incentive for companies to build wind power generation, and all the efforts by the government have been for nothing.

These days wind turbine sites are auctioned off to the highest (or, if you look at it from the government's perspective, lowest) bidder, and preparing for the auctions of the sites mentioned beforehand was one of the goals of this master's thesis: it was important to determine the cost of energy, in €/MWh, which would determine the auction bid. It should be noted that for the purposes of this master's thesis, a tariff and an auction result are often used interchangeably, due to the fact that they are the same thing in this context. An auction bid could be for instance a guarantee to sell electricity at 56 €/MWh, which the government would agree on for a certain number of years: this agreement would then for all intents and purposes work similarly to a support scheme in the form of a feed-in tariff, at least if the market price stays below the agreed price. A power purchase agreement (PPA) is a system where a party agrees to purchase power at a certain price for a certain period of time. After the auction, the winners might then after constructing the power plant enter into a PPA with the government if one is offered.

When a wind power plant is constructed and it enters a system with a FiT/FiP or a PPA, an agreement is made. The producer agrees to produce energy at the determined price, and the grid agrees to purchase energy at the same price, or to add a certain premium on top of the market price. The periods are often quite long, for instance 10 - 15 years, and this is why it is also important to have a couple of additional metrics while evaluating the importance of a project: the electricity price at that moment, and an estimate of how much the electricity price will increase for the lifetime of the projects, such as the next 25 years. This is important, since if the tariff (or agreement) is set at a relatively low price, and electricity prices are forecasted to increase heavily, the energy producer might be stuck producing energy at a net loss for the last years of the tariff agreement. For the first six months of 2017, electricity prices in Finland totaled an average of 31.96 €/MWh [20]. For the purpose of this master's thesis, an estimate for the rise in electricity prices will be a 2 % rise annually: a figure trying to mimic annual inflation, one that the European Central Bank tries to endorse. A simple example of the calculation is presented in Table 2.1 below.

Using this data, any one of the others can be calculated, in order to find the sweetspot and avoid any unnecessary difficulties. If the electricity price P is assumed

Table 2.1: A table showing the data of the simple calculations that were made in order to determine the optimal FiT amount, length and the annual rise in electricity prices for the project

Price	Increase	Size of the FiT/PPA	Duration of the FiT/PPA
P €/MWh	r %	S €/MWh	t years

to be 31.5 €/MWh, the annual increase in electricity prices r is 2 %, and S, the FiT or PPA, is 40 €/MWh, the calculations are as follows:

$$31.5 \text{ €}/MWh \cdot 1.02^t = 40 \text{ €}/MWh,$$

Which in turn can be solved as

$$t = \frac{log(\frac{40}{31.5})}{log(1.02)} \approx 12.06,$$

With this simple calculation it can be concluded that if the pruchase agreement is 40 €/MWh, the current electricity price is about 31.5 €/MWh, and the annual increase in electricity pricing is around 2 %, projects to be undertaken right now should be encouraged to get into support schemes or power purchase agreements under 12 years and be wary of contracts that have said condition for longer than 12 years (depending naturally on the electricity prices and the increase in those prices). All of this is done in the Excel files provided and was done on a regular basis when completing this project and this master's thesis. If a wind power project is deemed profitable without the need for external support (such as a premium or a tariff) it is said that wind power (or another form of energy generation) has reached *Grid parity* in that market: it is on par (in terms of costs) with other methods of producing energy, such as fossil fuels.

The general formula for the electricity that can potentially be generated is described in more detail than in Equation (2.1) by Narbel et. al (2014) as P_{pot} [22]:

$$P_{pot} = \frac{1}{2}\varphi_{air}\pi C_p(v)r^2v^3 \tag{2.4}$$

Where φ_{air} is the density of the air, $C_p(v)$ is mechanical efficiency, v is wind speed and r is the radius of the rotor. This does have limitations, however. Beyond the point of nominal power P_{nom}, the actual amount of produced electricity no longer increases, but stays the same until a cutoff speed of around 25 m/s: after this point, the blades need to be turned to such an angle that the wind power plant no longer produces electricity in order to protect its structural integrity and shield it from damage in case of excess wind speeds [23].

While the square of the rotor radius also seems to be a big factor that could be optimized, and certainly a larger rotor equals a larger swept area and therefore more power generation, there have been suggestions that increasing the radius or the lenght of the rotor beyond a certain point is not ideal, due to the increased weight of the larger rotor.[14] Another limitation to this is called Betz' law, a fundamental mechanical limitation to mechanical efficiency (sometimes also referred to as the Betz-Joukowski limit), which limits $C_p(v)$ to a maximum of $\frac{16}{27}$ or approximately 0.59 or 59 %. [24]. Current wind power plants can obtain an efficiency of around 40 - 50 % [23].

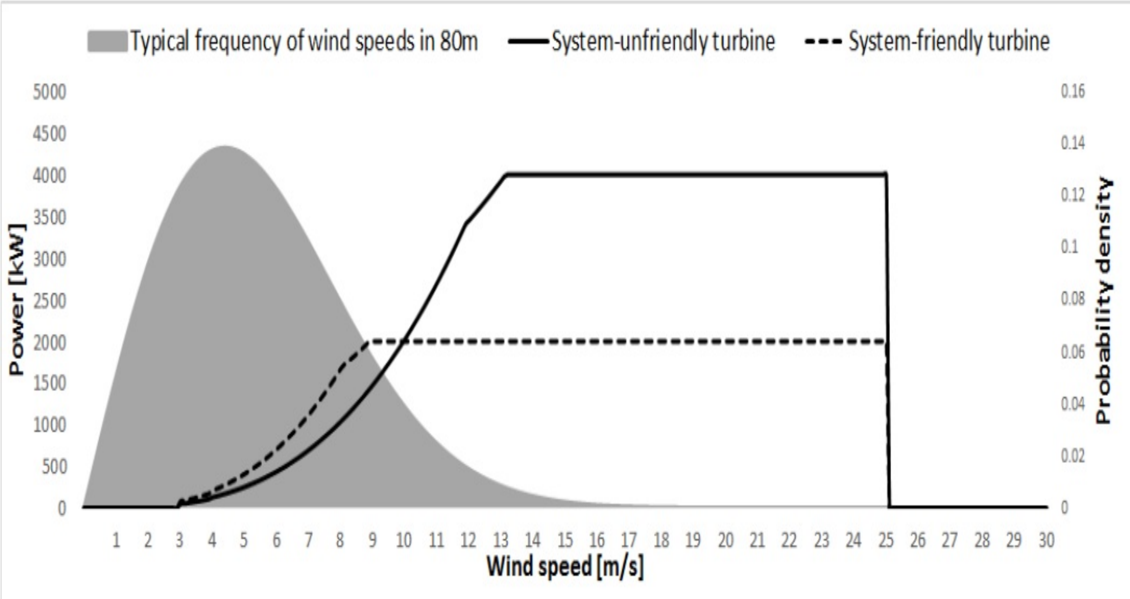


Figure 2.4: The wind power curve of a power plant with different options. The system-friendly turbine starts to produce electricity at the point of rated power a little earlier, between 8 and 9 m/s, while the system-unfriendly starts to produce later, but at a higher rated power at about 13 m/s [23]

Generally, tools that investors or companies that are looking into whether to build wind power take a look at are the aforementioned RoE as well as Net Present Value, a tool used to discount future money into value today using future profits as well as the rate of interest: accepting projects with a positive NPV is the equivalent of increasing your wealth by that amount today [25]. In its general form, NPV can be written as [25]:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \tag{2.5}$$

Where t is the amount of time periods, T is time, C_t stands for the net cash flow during the period stated earlier and C_o is the sum of all the investment costs.

In the case of a wind power plant being the subject of the investment, an investor can maximize the Net Present Value (NPV) of their investment N_i by keeping an eye on a few basic parameters [23]:

$$N_i = -\alpha_i + \sum_t \delta_t \omega_{i,t}(\pi_{policy_{i,t}} - \beta_t) \tag{2.6}$$

Where α_i denotes the turbine's fixed costs, $\omega_{i,t}$ is its generated electricity at a time of t. Discounting is done with the discount factor δ_t, variable operations and maintenance costs are β_t and π is the case-specific compensation per kWh.

Often investors look at a few specific things when making a financial analysis of a project, and whether to invest in that project or not. In this master's thesis, instead of Net Present Value, Return on Equity is used. The return on equity of a project can be seen as the earnings that an investor's money has made. In other words, if the RoE of a project is 2, every € in equity yielded 2 € of earnings. In this master's thesis, RoE was used to determine whether projects are worth investing in for European Energy, and that RoE was then subsequently optimized. Generally, RoE in economics can be presented as

$$Return\ on\ Equity = \frac{Net\ income}{Equity} \tag{2.7}$$

The result is often then multiplied by 100 to get a percentage value on the return on equity of a specific project. Because this master's thesis and European Energy use Return on equity as an indicator of whether to invest in a project or not, a significant factor to consider is also the cost structure of the investment. The amount of loan and equity, as well as the length of said loan can make a big difference when discussing things such as the net income and the equity of a project: increasing the amount of debt increases Enterprise value, as illustrated later.

Generally, with projects at European Energy, Return on equity is expected to be at least a certain figure, denoted in thesis as $n_{RoEpercentage} = n_{RoE}$, so that the returns for investors are high enough, and they are interested in the project. This figure is a standard figure in projects at European Energy, and is widely used in evaluating the appeal of a project. Generally investors might be attracted to projets that have a return on equity for for instance 6 %, and therefore that figure would have to be reached in projects in order to make them attractive to said investors.

As briefly mentioned before, the RoE of a project can be optimized among other things through the use of a loan. This decreases the amount of equity in Equation (2.7), which subsequently then increases the RoE: another way would naturally be to increase the net income. A part of this master's thesis was also to optimize the loan structure in the previously mentioned wind power plant sites in Ahvenneva, Honkakangas, Koiramäki and Mustalamminmäki.

As well as RoE, another important metric to measure the profit that European Energy would gain from the projects was used: Goodwill. Goodwill is a non-physical asset of a company or an entity, and it is widely used for accounting purposes [26]. The goodwill of projects for European Energy is expected to be around a certain figure per project too, denoted in this master's thesis and from now on as $n_{Goodwill} = n_{Gw}$. In this master's thesis, Goodwill and profit are used interchangeably.

An additional important economic term for this master's thesis is the Internal Rate of Return, or IRR. While RoE gives the aboslute yields of a project, IRR gives the yields over a certain amount of time. (RoE gives the amount of money earned as a percentage, while IRR gives the amount of money earned as a percentage annually, and for a certain amount of time.) Generally, IRR is defined as the interest rate that enables or sets the NPV of a project's cash flows equal to zero (Sometimes in the Excel files used by European Energy, RoE and IRR are used interchangeably, since they yield similar results.) In equation form, IRR is defined as [25]

$$NPV = 0 = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{2.8}$$

With the same notations as in Equation (2.5), but this time one solves the r, in order to get the IRR.

With the economic aspects being so largely dependent on the actual production of the wind power plants, and the production being so largely dependent on wind speed as can be seen in Equations (2.1) and (2.4), naturally the wind assessment methods used are crucial to the success of the project and the financial or cost optimization of the power plant in question. There are several different wind assessment methods and different exceendance probabilities. These probabilities are used to or by investors, who might only want to undertake projects with a certain degree of risk. They might also put additional strains on the loan structure of the projects, to be covered in a little more detail later. The exceedance probability generally used in this master's thesis was the P50, but others do also exist: the P75, the P90 and the P95. This division has to do with how certain the production of a wind power plant is. The P95 is the most likely scenario, with only a 5 % chance to deviate from the forecasted wind production numbers. This logic can be applied to the others as well, with the P75 having a 25 % chance of not reaching the forecasted energy production, and the P90 and the P50 having a 10 % and a 50 % chance respectively. The number most often used for this master's thesis is the P50, but some investors who want a very low degree of risk might require that a company uses the P90 in order to ensure a greater chance of getting their revenue. This does naturally mean lower production numbers, which affects the yield of the wind power plant. [27]

2.1.1 Grid Congestion and Adding Wind Power to the Grid

An important aspect (economically as well as technically) when designing wind power plant projects is transmission line capacity. Sometimes the capacity of the grid at a certain point has reached its transmission capacity limit, and therefore the amount and size of the wind power plant has to be limited to create a smaller strain on the grid. This might mean an increase in costs if the grid connection needs to be located elsewhere, due to the cost of the cable and other works. [14], [15]

Another way of going about this would be strengthening the grid at the point of connection. In addition to the voltage, the point of common coupling (PCC) is an important aspect. Grid strength is defined as the short circuit power of a grid, represented in Figure 2.5.

$$S_k = 3 \cdot |Z_k| \cdot \ I_k^2 = \frac{U_n^2}{|Z_k|} \tag{2.9}$$

And in equation form the Short circuit power S_k can be calculated with the short circuit current I_k, the impedance Z_k, and the voltage $\frac{U_n}{\sqrt{3}}$, as presented in Equation 2.9 below.

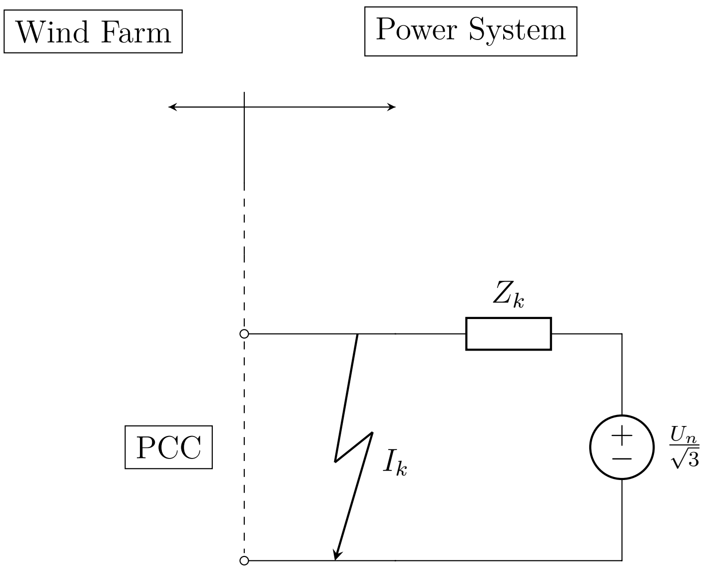


Figure 2.5: PCC and the short circuit power, adapted from [29]

In other words, grids with a small impedance Z_k have high short circuit power: they are strong. Rural areas (where wind power plants are often built to decrease visual and noise pollution as well as other impacts) often have little need of a strong network, which might cause issues: weak grids might quickly reach the thermal limit of the cables, due to small conductors. In addition to the fact that rural areas might already have a weak grid, the fact that wind power plants are often located far away from housing and therefore the grid, increasingly long cables lead to increased impedance, which might lower grid strength even more [28]. Strengthening the grid would mean, as according to Equation 2.9, decreasing the amount of impedance Z_k, or increasing the voltage U_n. To get around this problem, distribution companies often prefer generation to be connected to a higher voltage, where the impacts are negligible. This is rarely done, however, due to the increased costs that strengthening the grid (increasing the voltage of the grid at a certain point) would mean [29], [30] [31].

Other than a general view of how wind power projects are usually planned, there exists no coherent story or viewpoint for how to fully optimize the cost efficiency of wind power plants within European Energy. The data used and required comes from many different sources, and this master's thesis focused not necessarily on how to obtain that data but rather putting all the different information together. This master's thesis aimed to give a comprehensive understanding of what are the most critical components when trying to bring costs down while preparing for a wind power plant auction, while keeping profits as high as possible.

2.2 Stages in Wind Power Plant Development

It should be noted that a wind power plant project construction process is often a lengthy one, and consists of several different phases or stages. This thesis only really focuses on one of those phases, as the others can vary from time to time due to regulations and the different authorities one is dealing with and are challenging to optimize. These processes are presented in Figure 2.6 below, and the relevant part is highlighted in red. While a lot of phases are out of the scope of this master's thesis, the bureaucratic and lenghty process that is applying for and trying to build a wind power plant is presented quite accurately in Figure 2.6, although the figure is from [14], written in 2007 from the perspective of the Swedish wind power industry, and it could be argued that the whole industry has undergone a lot of changes to the development process. At least for European Energy, the focus has shifted from focusing on the permiting process to focusing on the financial aspects, as support schemes have diminished and power prices have come down [20].

2.3 Wind Power and the Cost of Wind Power in the Future

As can be seen from previous chapters, wind power has advanced significantly over the past years. There are numerous ways in which wind power plants might still be improved, including improving on the aspects discussed earlier: both performance (in terms of energy output) and reducing costs. Performance improvements for wind power plants could include, among other things, higher heights (more wind speed), larger blades (a larger swept area) and superconducting magnets (thermal losses are minimized). A possible future trend for wind power plants is depicted in Figure 2.7 below. Improving the capacity factor of the wind power plants is also something that could be done: CF is a key factor in determining the price of wind energy [32]. In addition to the methods mentioned previously, advanced control methods and smart-blades in order to maximize performance could be utilized.

In addition to that, the energy consumption of these control methods could be minimized, so that a larger part of the energy produced by the wind power plant actually makes it to the grid. Reliability and availability of wind power could also be improved, as the weather forecasting tools in use right now are not perfect.

As mentioned previously, the theoretical efficiency of a wind power plant is obtained with the Betz limit (around 59 %), but since current power plants do not quite achieve that level (only around 50 %), there are some improvements that could be made to the control methods of a WPP, at least in theory, to improve the mechanical efficiency of wind power plants. Naturally, losses in a wind power plant could always be decreased, with smaller transportation lengths for the produced electricity, as well as cables that are more suitable for the job, more efficient generators and so on. This would work in trying to decrease the indirect costs of wind power plant construction.

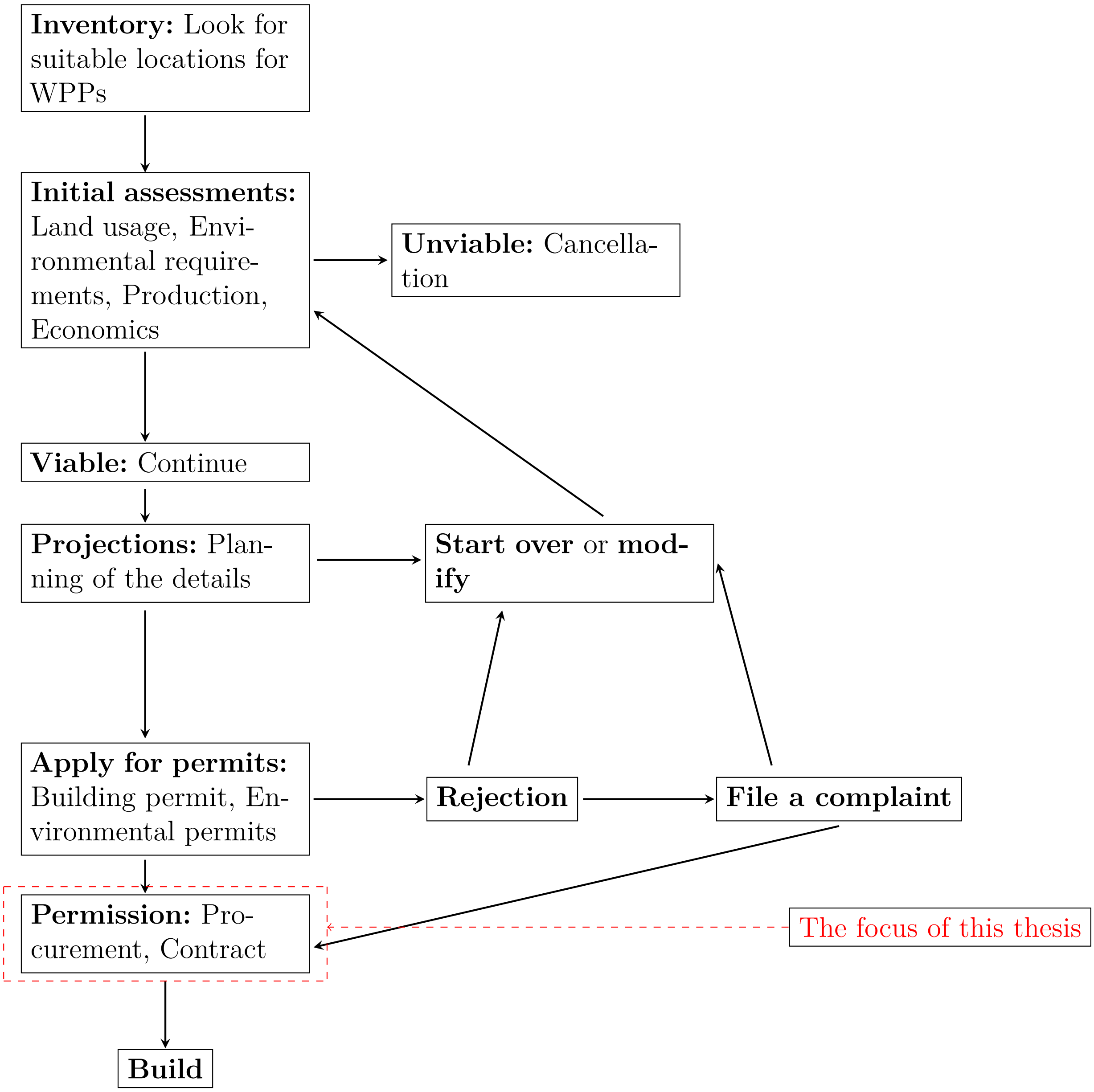


Figure 2.6: The stages of a wind power plant project, the focus of this thesis is marked in red. Adapted from [14]

Reducing costs in wind power plants could be, similarly, done in many different ways. Although materials are not the focus of this master's thesis, advanced materials could of course be utilized in order to bring direct costs down, as well as improving the process starting from the foundations and the construction as well as maintenance. Weight and therefore the difficulty of the turbine installation process could also be reduced by going for fewer blades, for instance in the form of a 2-blade solution (which would also, naturally, slightly decrease production). Other, out-of-the-box designs could also be implemented, such as floating or high-altitude wind power

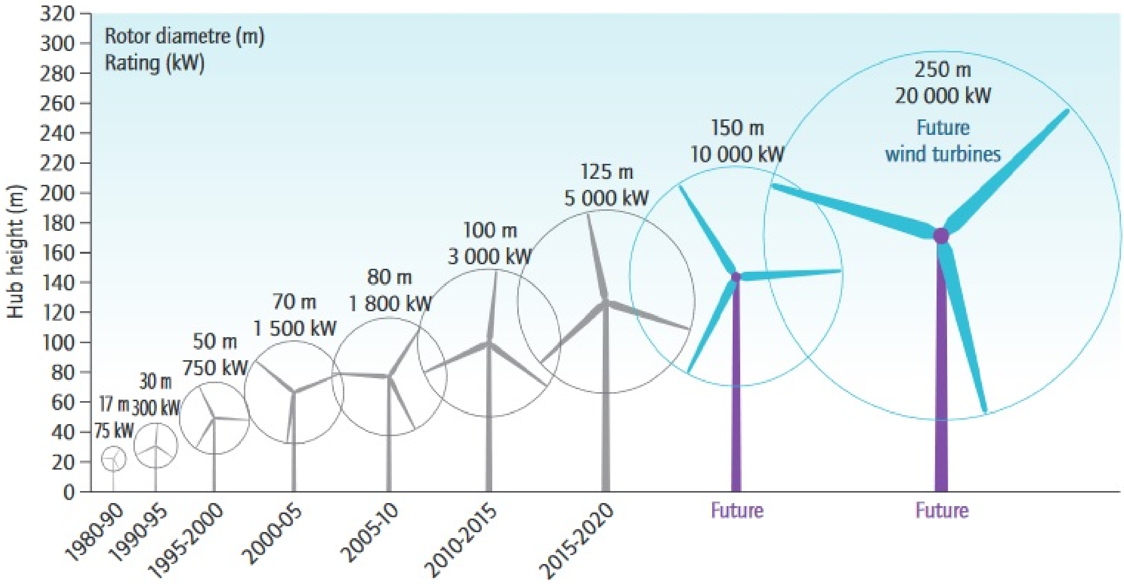


Figure 2.7: The future developments of wind power plants [36]

concepts [18]. A different approach would be educating people on the properties of wind power plants. Research by Firestone et. al (2007) suggests that people often associate wind power plants with negative side effects, and might be inclined to think that land adjacent to a wind power plant decreases in value [33]. This could have a positive (lowering) impact on land lease or rent prices for the wind power plant operators, as knowledge of the fact that there are very few adverse effects to being neighbours to a wind power plant or a wind farm would be more widespread.

Increasing the profit that comes from a wind power plant could also be improved by for instance a more advanced carbon trading scheme, as mentioned before. The Kyoto Protocol introduced a mechanism in which wind energy producers can claim certified emission reduction (CER) credits for a project due to the CO_2 that is being offset by an alternative form of energy production. [34]

A lot of these methods or suggestions are beyond the scope of this master's thesis as the focus is only on a few financial and technical aspects of wind power plant cost optimization: the viewpoint of a constructor or a developer, not the manufacturer of wind power plants. They were instead mentioned as future design considerations of wind power plants and as ways to exceed what this master's thesis focuses on. It could also be argued that the future of wind power is not onshore but offshrore wind power plants. In the beginning of the year 2017, Europe had a total installed capacity for offshore wind farms of over 12 000 MW, and over 1600 MW of that was installed in 2016. While 2016 saw a sharp decline in installed offshore wind power capacity (48 % less than in 2015), the future still looks very bright for both onshore and offshore wind power. [35]

After taking a general look into the operation of wind power plants, their cost structure and their production, and identifying the most important factors for both the profit of a wind power plant and the most important factors regarding the costs of a wind power plant, the Cost of Energy, and its main components could be identified. The main components included hub height and wind speed in terms of production, and many different things for the costs, such as the height (and weight) of the turbines, grid connection accessibility, grid congestion, land lease or purchase and the foundation. In addition to these things, the chapter examined the possible future developments of wind power plants. The next thing the thesis takes a look at are the research methods and material used during the writing process.

3 Research Material and Methods

This chapter sheds some light on the materials as well as the methods used in the completion of this master's thesis, both in the initial research phase and the actual optimization phase that followed. Due to the nature of the thesis and the fact that the thesis was consctructed as a preparation for an upcoming wind energy auction in Finland, some of the actual figures have been changed.

3.1 Material

The main materials for this study were foundational works in the economics of wind power and its optimization. Many fundamental books in the field of wind energy have been written over the years that were used, with the support of newer scientific publications. A cornerstone through which the basis and understanding required in order to write this master's thesis was obtained was Vindkraft i teori och praktik also translated to English as Developing Wind Power Projects: Theory and Practice. In addition to this, many academic studies have been conducted and written both around the cost structure of wind power plants, as well as honing their technical attributes, which were used to obtain a lot of valuable data, such as many annual outlooks and predictions by organizations such as the Global Wind Energy Council, and the International Energy Agency.

Actual data from real wind power parks was also used to obtain realistic results, as well as ones that can directly be applied to the real world: actual offers from wind turbine manufacturers, which were then subsequently compared and optimized.

The idea of this master's thesis was to first look at the existing data in terms of cost optimization, and then do the necessary simulations and calculations with the new offers and information in mind to find the optimal result. The fact that actual offers were used means that information was acquired in several parts: initial data such as the power curves were obtained in order to gain an understanding of the potential of the offers' turbines, after which further inquiries were made to the respective manufacturers to get more detailed information about the turbines, such as an idea of the pricing as well as delivery times and foundations.

3.2 Methods

The methods used in this thesis work were mainly computational ones, with heavy reliance on the WindPRO software, but more importantly, Microsoft Excel. The WindPRO software was utilized to do some of the mathematical heavy lifting as well as a lot of the models that were produced and used. The actual cost optimization was done with Microsoft Excel which was used was used, with the help of ready-made templates, in order to make easily accessible and changeable data which then enabled finding possible sweet spots in the optimization of the costs of wind power plants. Excel functions, such as finding the IRR of a project, were used to crunch the numbers on several projects simultaneously in order to find the optimal result.

3.2.1 WindPRO

The WindPRO software was used in this work to obtain realistic data from actual wind power plants and wind power plant locations. It is widely used by professionals working in the field of wind energy generation and construction. The WindPRO software is a program made specifically for wind power calculations by EMD International A/S, a company that specializes in wind energy software and operates around the world. The WindPRO software can be utilized to answer questions such as the amount of energy produced by the turbines at the sites as well as how to optimally use the site in terms of energy yield, as well as the consequences that arise from connecting a power plant to the grid. WindPRO can also be used to do an enviromnental assessment report, which includes noise, flicker and visual interference data. Finally, WindPRO also has economic and financial tools that can be used to calclulate the cash flows and balance sheets of different projects. In addition to the calculations, WindPRO can be used to obtain a lot of the documentation needed when constructing a wind power plant. [37]

The WindPRO software was utilized in the completion of this project and this master's thesis in multiple ways, in order to obtain reliable data that could be used in order to calculate the required numbers and values from a technical standpoint. WindPRO was used to estimate wind speeds at the total heights specified earlier, which is, as shown in Equation 2.1, is an integral part of the production of a wind power plant. Like previously mentioned, WindPRO also used location data and requires coordinates of not only the sites, but of the specific wind turbine locations themselves, to search the internet for wind assessments and area topography. The area has, naturally, significant impacts on the possible wind speeds, with highly forested areas often seeing less wind than more open areas. In WindPRO, these are divided into Orography and Roughness. After inserting geographical data to orography and roughness, the aforementioned geographical location data can be added, after which WindPRO will proceed to search the web automatically for wind pattern data. After that step, data from one's own measurements can be added: here, the SODAR data collected was used as an input for WindPRO, which the software then could utilize. After putting in the location data, geographical formation as well as online wind data and measurement wind data, the power curve could be plotted with different heights.

An illustrative picture of the kind of data that WindPRO provides is presented in Figure 3.1 below.

As can be seen in Figure 3.1, WindPRO provides very detailed data about things such as production, at different individual turbines (denoted here as 1A, 2A, 3A and so on), as well as the efficiency of the process and the wind speed at the location. These are produced by a part of the software called the PARK module, which includes the many parts, such as the Main Result (represented in Figure 3.1). Production Analysis divides the energy production to different wind directions (or sectors), represented in Figure 3.4. Wind Data Analysis (Partly presented in Figure 3.2) provides detailed information about statistics as does Wind Statistics Info, while Park Power Curves presents the calculated power curves for the turbines

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10,0% [MWh]	GROSS (no loss) Free WTGs [MWh/y]	Park efficiency [%]	Specific results¤) Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	127 662,4	114 896,2	137 795,2	92,6	42,0	14 362,0	3 683	7,5

¤) Based on Result-10,0%

Calculated Annual Energy for each of 8 new WTGs with total rated power

Links	WTG type Valid	Manufact.	Type-generator	Power, rated	Rotor diameter [m]	Hub height [m]	Displacement height [m]	Power curve Creator	Name	Annual Energy Result [MWh]	Result-10,0% [MWh]	Park Efficiency [%]	Mean wind speed [m/s]
1 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	16 293,3	14 664	94,68	7,48
2 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	15 601,1	14 041	91,46	7,43
3 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	15 389,5	13 851	89,51	7,47
4 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	15 848,8	14 264	91,11	7,52
5 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	16 284,3	14 656	94,11	7,51
6 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	15 602,7	14 042	90,24	7,50
7 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	16 199,1	14 579	94,13	7,47
8 A	Yes				142,0	144,0	0,0	USER	Mode 1 - Calculated - Std. 107 dB - 05-2017	16 443,6	14 799	95,95	7,46

Figure 3.1: An illustrative picture of a part of the data provided by WindPRO

from different directions. WTG Distances gives the turbines' distances from one another (information that might be useful if it turns out that one or several of the turbines are obstructing each other, and the layout needs to be redesigned. These kinds of losses related to a turbine being partially blocked are called *Wake losses*), a map of the area as well as wind statistics info, which specifies the type of data used. PARK- WTG Distances can be seen in Figure 3.3. Other modules include things such as MCP (Measure, Correlate, Predict) as well as the noise models briefly mentioned previously, but they were neither nor the interest nor in the scope of this master's thesis.

Using the data provided by turbine manufacturers A, B, C and D, WindPRO also provides an estimate of the capacity factor, and overall efficiency, and a lot of supportive graphs and figures, such as energy and frequency roses. Since a wind power plant can have the wind blow from any direction, an energy or frequency rose shows the dependency of certain parameters (such as frequency and energy) on the direction that the wind is blowing from.

The Weibull distribution of this specific power plant as well as the energy rose is presented in Figure 3.2 below. The Weibull distribution figure that WindPRO yields is a probability distribution of the wind speeds, illustrating the most commonly experienced wind speeds in percentage of frequency. The energy rose, as mentioned before, illustrates from which direction the wind is blowing when energy is produced (together with the frequency rose: in order to calculate the annual energy yield of a wind power plant, the cube of the air speed is multiplied with the frequency and then they are all added up [14]). WindPRO uses actual wind measurement data (In this case, Sound Detection and Ranging (SODAR) data was used. SODAR is a wind speed measurement method that transmits and detects sound and how it scatters due to turbulence in the atmosphere: other methods include things such as Light Detection and Ranging (LIDAR) [38].) as well as ready-made data made available by studies over the years, that the software automatically searches for from the web

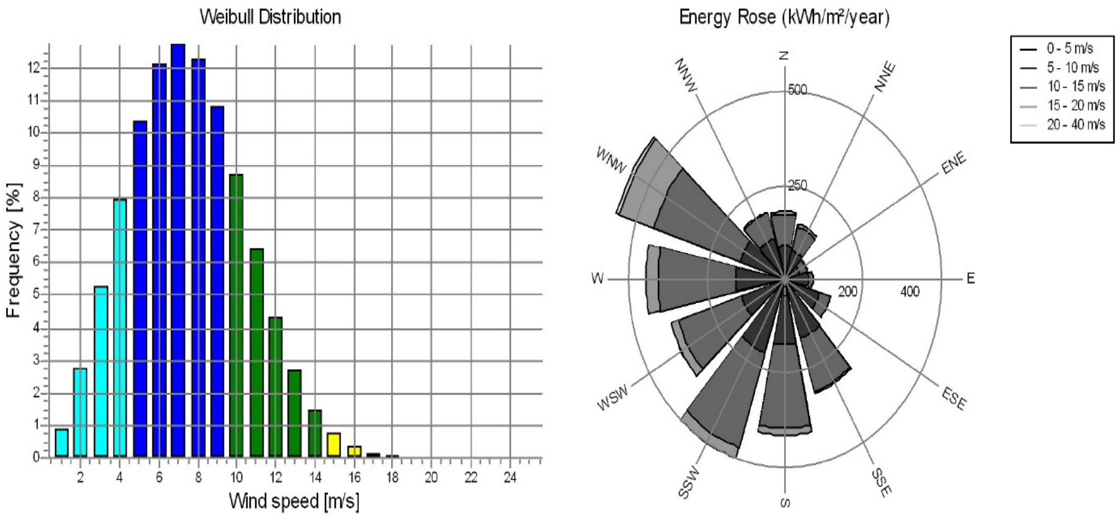


Figure 3.2: An illustrative picture of an energy rose provided and the Weibull distribution by WindPRO, found in Production Analysis

PARK - WTG distances

Calculation: Karstula Mustalamminmäki

WTG distances

	Z	Nearest WTG	Z	Horizontal distance	Distance in rotor diameters
	[m]		[m]	[m]	
1	184,8	2	177,5	650	4,6
2	177,5	3	183,1	579	4,1
3	183,1	6	180,0	468	3,3
4	180,0	8	182,5	578	4,1
5	185,0	4	180,0	618	4,4
6	180,0	3	183,1	468	3,3
7	179,2	6	180,0	487	3,4
8	182,5	4	180,0	578	4,1
Min	**177,5**		**177,5**	**468**	**3,3**
Max	**185,0**		**183,1**	**650**	**4,6**

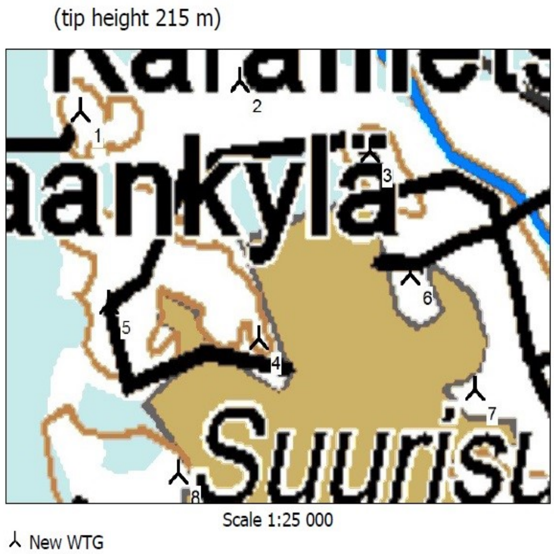


Figure 3.3: An illustrative picture of the WTG Distances part by WindPRO

in order to obtain data for wind measurement. WindPRO also takes in as an input the location data, that it uses to determine approximately the height of the objects as well as terrain (called roughness in wind projects) that might affect wind speeds in the area. The WindPRO software is also capable of providing a lot more data than just the MCP (Measure, Correlate, Predict) data used here. MCP also gives a brief overview of what the WindPRO software was used to do here: measure and estimate the wind speeds, correlate them with data, and then predict future speeds and therefore production. Although WindPRO gives many different kinds of data and results, the Main Result section was the one focused almost exclusively on, since it includes most of the interesting parts in terms of optimizing the cost structure of wind power plants.

PARK - Production Analysis

Calculation: Karstula Mustalamminmäki (tip height 215 m)**WTG:** All new WTGs, Air density 1,236 kg/m

Directional Analysis

Sector		0 N	1 NNE	2 ENE	3 E	4 ESE	5 SSE	6 S	7 SSW	8 WSW	9 W	10 WNW	11 NNW	Total
Roughness based energy	[MWh]	7 533,8	6 296,0	3 897,4	4 816,8	7 983,3	14 086,7	17 210,6	19 795,0	14 270,5	15 900,9	16 982,2	9 022,0	137 795,2
-Decrease due to array losses	[MWh]	443,3	484,6	248,6	585,2	696,0	1 750,5	773,8	1 229,9	646,9	1 147,5	946,2	1 180,2	10 132,8
Resulting energy	**[MWh]**	**7 090,5**	**5 811,4**	**3 648,8**	**4 231,6**	**7 287,3**	**12 336,1**	**16 436,8**	**18 565,1**	**13 623,6**	**14 753,4**	**16 036,0**	**7 841,8**	**127 662,4**
Specific energy	[kWh/m²]													1 008
Specific energy	[kWh/kW]													4 092
Decrease due to array losses	[%]	5,9	7,7	6,4	12,1	8,7	12,4	4,5	6,2	4,5	7,2	5,6	13,1	7,35
Utilization	[%]	32,1	32,0	35,0	37,1	37,1	30,6	29,2	29,3	30,0	28,3	24,7	31,8	29,8
Operational	[Hours/year]	511	521	323	500	611	809	889	1 103	772	864	949	585	8 437
Full Load Equivalent	[Hours/year]	227	186	117	136	234	395	527	595	437	473	514	251	4 092

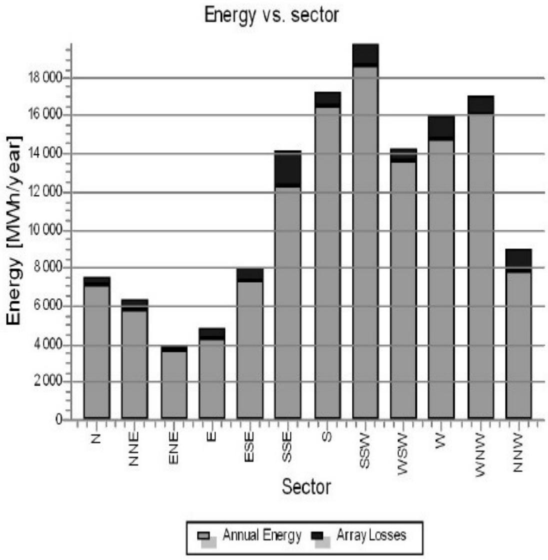


Figure 3.4: An illustrative picture of the Production Analysis part by WindPRO

3.2.2 Microsoft Excel

Microsoft Excel was also used in this study to crunch the numbers after acquiring data from the WindPRO software, as well as inserting other information to the excel sheets. The Excel sheets were also the reason why tariff or PPA price is used interchangeably with the auction price in this thesis, as Excel does not differentiate between a tariff of a certain size and duration and a winning bid of the same size and duration.

As mentioned previously, ready- made sheets provided by European Energy in Excel were utilized in order to easily be able to manipulate the numbers and costs of a wind power plant in order to find the most cost efficient way of doing things as well as maximizing profits. (The Excel sheets were ready-made, but error checked and partly corrected by the author of this thesis) While this was a big help in organizing the task of this master's thesis and saved a lot of time, it did also mean that some of the parts of the Excel sheet are not integral to the successful completion of this master's thesis or the succesful completion of the project. This data includes many things in some of the financing aspects of the project, such as the more detailed financial breakdowns of the excel such as DSRA, DSCR and DSRF, to be covered later in a little more detail.

The Excel utilized is divided into separate sheets that all provide important information integral to the succesful completion to the project. For each of the four projects mentioned before (Ahvenneva, Honkakangas, Koiramäki, Mustalamminmäki) several separate sheets exist, as well as a couple of sheets that hold important information of all the projects. The Excel sheets are as follows: Project Information, ConsolidationFI, Base Assumptions, Base Calculations, Base Financing and Sens. An example of the data used in the Project information Excel sheet is presented in Figure 3.5 below. In total, the Excel sheet used had Base Assumptions, Base Calculations and Base Financing for all of the projects, but as mentioned previosuly, only one of the sites is presented here: the WindPRO data gathered supported the notion that the sites are similar enough for this kind of simplification: in terms of roads, grid connection and the cost of energy, among other things.

Park name	Revenue, Grid loss, %	Revenue, Method incertainty / other effects, %	Revenue, Method incertainty / other effects, comments	Revenue, Total losses, %	Power, Price area	Power, Market price, EUR/MWh	Power, Subsidy scheme	Power, Feed-in-tariff duration period, years (or PPA)	Power, Feed-in-tariff price, EUR/MWh (or PPA)	Power, Feed-in-tariff price, Date of FiT start	Power, index
FI Project # A: Jeppo	0.0%	9.4%	na	9.43%	FI	28.0	Scheme 2017	12.00	83.5	01/07/2017	2.50%
FI Project # B: Haukineva	0.0%	9.6%	na	9.63%	FI	28.0	Scheme 2017	12.00	83.5	01/07/2017	2.50%
FI Project # C: Vihreäsaari	0.0%	0.0%	na	0.00%	FI	28.0	Scheme 2017	12.00	83.5	01/07/2017	2.50%
FI Project # D: Ahvenneva	1.0%	4.0%	na	7.79%	FI	31.5	Scheme 2019	0	0	01/01/2019	2%
FI Project # E: Honkakangas	1.0%	4.0%	na	7.79%	FI	31.5	Scheme 2019	0	0	01/01/2019	2%
FI Project # F: Koiramäki	1.0%	4.0%	na	7.79%	FI	31.5	Scheme 2019	0	0	01/01/2019	2%
FI Project # G: Mustalamminmäki	1.0%	4.0%	na	7.79%	FI	32.6	Scheme 2019	0	-	01/01/2019	0%
FI Project # Ø: Kokkola	*0.0%*	*0.0%*	*na*	*0.00%*	*FI*	*28.0*	*Scheme 2017*	*12.00*	*83.5*	*01/07/2017*	*2.50%*
FI Project # Ø: Tetrituuli, alt 1	*0.0%*	*0.0%*	*na*	*0.00%*	*FI*	*28.0*	*Scheme 2017*	*12.00*	*83.5*	*01/07/2017*	*2.50%*
FI Project # Ø: Tetrituuli, alt 2	*0.0%*	*0.0%*	*na*	*0.00%*	*FI*	*28.0*	*Scheme 2017*	*12.00*	*83.5*	*01/07/2017*	*2.50%*
FI Project # Ø: Tetrituuli, alt 3	*0.0%*	*0.0%*	*na*	*0.00%*	*FI*	*28.0*	*Scheme 2017*	*12.00*	*83.5*	*01/07/2017*	*2.50%*

Figure 3.5: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of the Project information, with the relevant parts highlighted in red, and with the FiT/PPA scheme set to 0

The Project Information Excel sheet has several cells of information, and this is the template used by European Energy in order to determine whether a project is worth investing in. As can be seen in Figure 3.5, the sheet shows the projects regarding this master's thesis, as well as previous projects that were or were not undertaken. The division of the information on this excel sheet that uses this information to then do the actual calculations, includes Wind Farm Information, which includes things such as the latitude and longitude of the wind farm, as well as the hub height, rotor diameter and the total height of the turbine, including the manufacturer. Miscellaneous assumptions includes things such as an estimate of the rate of inflation, currency conversions and so on. Taxation, like the name states, includes things such as the corporate tax rate, first years of deduction and so on. Wind assessment has to do with the wind speed at hub height, wind measurement methods (mentioned earlier), gross production of each method respectively, losses and revenue. Power includes estimates of the market price of power, size and duration of the Power Purchase Agreement. Both Certificate as well as LECs and GoO are optional parts of the Excel, and are not always taken into account. Levy Exemption Certificate (LEC) was an old support scheme by the British government, and GoO refers to Guarantee of Origin, a price payed for energy generated in a certain manner. The Grid benefit refers to a system that's used in for instance Sweden, where a grid benefit price can be paid to electricity producers in certain areas, in order to encourage distributed production of energy. CAPEX refers to Capital Expenditures, which includes all kinds of non-operational costs, such as the cost of legal and technical advisors, EPC (engineering, procurement and construction) costs, the cost of the turbines themselves, legal fees and so on. OPEX refers to Operational Expenditures, which refers to things such as the cost of the land leases, maintenance costs of the turbines including both a base service fee as well as a production-based fee, used by some manufacturers, insurances for the turbines as well as the generators and so on.

CAPEX and OPEX both held important information when it comes to the cost structure of the project, and these would be the values manipulated later on to determine the most important components in the cost structure of a wind power plant. CAPEX more specifically included things such as project rights, development fees, group fees, permits and licences, purchase of land (more commonly in projects with European Energy, lands are leased instead), purchase of neighbouring real estate (not often done, due to the additional costs), construction costs including things such as the foundation, underground and civil works, fees from technical, legal and financial advisors, as well as other running costs. OPEX, on the other hand, included things such as insurance for the turbines, technical and commercial management, technical surveillance, administrative fees, handling fees, bookkeeping fees, grid usage fees, other costs and balance costs for the grid (in case there is a difference between purchased and consumed electricity). These were later analyzed in detail in Chapter 4.3.1 in order to find the most important factors.

Finally, Financing refers to the financing of the project: how the project is financed, the size and duration of the loan, interest rates and so on. The Excel file uses the methods mentioned in Chapter 2 to make the actual calculations, such as the production.

An illustrative picture of some of the information in ConsolidationFI is presented in Figure 3.6. Again, the Excel sheet itself has a lot of information, only some of which is presented in Figure 3.6. The sheet ConsolidationFI on the Excel file used for this master's thesis includes a consolidated overview of Finnish projects, and the projects that this master's thesis focuses on. ConsolidationFI uses data inserted on the sheet Project information to calculate a lot of figures and numbers essential to the succesful completion of a project. ConsolidationFI includes important figures

BALANCE SHEET			
ASSETS		Total	18,141,160
		Empty	-
		FI Project # G: Mustalamminmäki	17,565,334
		Empty	-
		Empty	-
		DSRA	575,826
EQUITY			4,775,758
DEBT			13,365,402
RETURN CALCULATIONS			
Project IRR			
ROE - explicit		12.0451%	-4,775,758
ROE - implicit	Unleveraged = 6%	4.6004%	-21,703,191
	leveraged = 11.67%		
		Goodwill	8,197,172
		Enterprise value, DSRA	12,754,434

Figure 3.6: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of ConsolidationFI

such as a balance sheet including estimates for production, revenue, taxes and profit, as well as the actual RoE calculation, both with and without debt, as well as a breakdown of some of the financial aspects. These include Debt Service Reserve Account (DSRA), Debt Service Reserve Facility (DSRF), as well as Debt-Service Coverage Ratio (DSCR). These are used mainly by the financial department of European Energy, and are neither the interest nor in the scope of this master's thesis. ConsolidationFI is also the sheet that shows the RoE of the project or the projects (each one and any mix of the projects can be chosen separately), which is one of the primary points of interest in this master's thesis. (The actual RoE is in the box in white, while target RoE is in the yellow box) Taking a quick glance at the ConsolidationFI page also gives a quick idea whether it is feasible to try to get into a certain FiT/FiP scheme or PPA: the Excel allows (on the Base Calculations sheet, to be explained in more detail later) the projects to either be on an FiT scheme of certain size and duration, but it also allows selling directly to the markets with no FiT. If the RoE is higher when setting no FiT than it is when putting such a scheme in place, one can directly conclude that a certain FiT/PPA scheme is not worth getting into. Most importantly, in addition to the RoE and goodwill of the projects, ConsolidationFI had the production of the projects, as well as the enterprise value, which allowed the calculation of the cost of energy for the projects: a crucial part in the auction bid.

The Base Assumptions sheet of the Excel is a collection of the information provided in the Project information sheet, but in a more approachable form. An illustrative picture of the Base Assumptions is presented in Figure 3.7. Base Assumptions presents in a more visually pleasing way the project in question (in the case of Figure 3.7, project # G, Mustalamminmäki). Wind farm information, miscellaneous assumptions, information about taxation, wind assessment, financing, CAPEX, production, power, grid benefit, GoO and LEC as well as OPEX are presented, similarly as was done with the Project information sheet earlier, as well as a breakdown of the different

WIND FARM INFORMATION	unit			
Site		FI Project # G: Mustalamminmäki		
Country	(country code)	FI		
Hub height	(m)	145		
Rotor Diameter	(m)	150		
Total height	(m)	220		
Manufacturer		Manufacturer D		
Model/type		Turbine type D		
Capacity	(kW)			
No. of turbines		8		
Total installed capacity	(kW)			
Construction start (DD-MM-YYYY)	(date)	31/12/2018	<=>	31/12/2017
Construction period (rounding up to nearst quart	(months)	-	<=>	31/03/2018
Expected commencement (DD-MM-YYYY)	(date)	31/12/2018	<=>	31/12/2018
Operation period	(years)	25	<=>	31/12/2043

MISC ASSUMPTIONS				
Valuation date (DD-MM-YYYY)	(date)	31/12/2018	<=>	31/12/2018
Inflation		2.0%		
Forex	EUR/EUR	1.00		

CAPEX	Tax depreciable	%	TOTAL
TOTAL INVESTMENT (external costs)	Yes	89%	11.09
EPC / PMA	Yes	8%	1.00
DSRA	No	3%	0.40
TOTAL INVESTMENT		100%	12.49
Share of CAPEX which is account depreciable		97%	12
Specification: Initial value of foundation, steel tower, etc., pr. turbine (used for tax calculation)			0.72

FINANCING[1]	Yes				
Lender	% of total investment		Interest	Type	Maturity (years)
Loan#1	73.7%		2.00%	Serial	15.0
Loan#2	0.0%		0.00%	0	-
Loan#3	0.0%		0.00%	0	-
Share of debt:	73.7%	Weighted interest rate:	2.00%		

	Amount	Share
Debt	9	73.70%
Equity	3	26.30%
Total investment	*12*	*100.00%*

Figure 3.7: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of the Base Assumptions

costs. It should also be noted that Figure 3.7 clearly states the amount of loan in terms of the total investment, in other words it allows for clear iteration of the loan structure in order to optimize the RoE as mentioned before.

Calculations

FI Project # G: Mustalamminmäki

Quarter start 1

Quarter end 100

BUDGET QUARTER		0	1	2	3	4	5	6	7	8	9
DATE		31/12/2018	31/03/2019	30/06/2019	30/09/2019	31/12/2019	31/03/2020	30/06/2020	30/09/2020	31/12/2020	31/03/2021
Line item	*Unit*										
Production	MWh		29,605	29,605	29,605	29,605	29,605	29,605	29,605	29,605	29,605
Market prices											
Power, market price	EUR/MWh		32.60	32.61	32.61	32.61	32.61	32.62	32.62	32.62	32.63
Grid benefit	EUR/MWh		-	-	-	-	-	-	-	-	-
LEC	EUR/MWh		not used	not used	not used	not used	not used	not used	not used	not used	not used
GoO	EUR/MWh		0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Market settlement price	EUR/MWh		32.90	32.91	32.91	32.91	32.91	32.92	32.92	32.92	32.93

Figure 3.8: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of the Base Calculations

A part of the Base Calculations sheet is presented in Figure 3.8. Base Calculations is a breakdown of the costs and production, based on the data inserted earlier on the other sheets. Base Calculations again includes things like market prices, subsidy price and settlement price, giving the amount of estimated revenue. It also includes a breakdown of the OPEX, as well as the financial aspects of the project. These all are included for the whole lifetime of the project, assumed here and in all cases to be 25 years.

Loan #1	
Principal:	65%
Payout date:	31/12/2018
Maturity date:	30/12/2033
Years to maturity:	15.01
Rate, period 1	
Nominal rate	1.80%
Until date (including)	30/12/2033
Until year (including)	15.01
Rate, period 2	
Nominal rate	1.80%
Until date (including)	30/12/2033
Until year (including)	15.01
Type:	Serial
Yeary payments:	4
Grace peeriod:	No
End of grace period:	na
End term:	60.00

Figure 3.9: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of the Base Financing

A part of the Base Financing sheet is presented in Figure 3.9. Base Financing is an important aspect to the functioning of the projects, as well as whether to undertake the projects in the first place. Financing illustrates in a visual and intuitive way the viability of the project's financing and its financing structure, and whether it is a good idea to undertake the project in the first place. It also allows easy manipulation of the figures in order to obtain the most efficient way of financing through a simple iteration process: changing the numbers and shares is straightforward, and the results are presented clearly on the ConsolidationFI sheet.

A part of the Sensitivity sheet is presented in Figure 3.10. Sens is included in the Excel only as a baseline and guidance to understand the offers from the wind turbine manufacturers. It gives a rough estimate of what European Energy would be willing to pay for a turbine of a certain rated power: both in terms of the actual cost of the turbine as well as service costs. As mentioned before, sometimes turbine costs are seemingly lower, but the actual costs can be hidden in the service costs. When looking at the Sens sheet, it was important to keep in mind the target goodwill of n_{Gw} €. This could be achieved by looking at the corresponding price and service cost for a turbine, as well as the profit above the table in the figure. This meant, because the profit is represented as a multiple of the required profit, that for instance a combination of service cost and WTG price here that adds up to 1 would be a profitable investment, such as 3.8 M€ for the turbine and 60 k€ per year as per Figure 3.10.

For clarity, the different Excel sheets and their mutual dependency is presented

Enterprise Value	13.38							
Total Profit	2.25							
CoF	-0.16							
"Pure" profit befor tax	**2.09**							
PROFIT FOR EE IN MEUR								
	WTG price							
	3,300,000.00	3,400,000.00	3,500,000.00	3,600,000.00	3,700,000.00	3,800,000.00	3,900,000.00	4,000,000.00
60,000	0.48	0.21	-0.06	-0.33	-0.60	-0.87	-1.14	-1.41
70,000	0.22	-0.05	-0.32	-0.59	-0.86	-1.13	-1.40	-1.67
80,000	-0.04	-0.31	-0.58	-0.85	-1.12	-1.39	-1.67	-1.94
90,000	-0.30	-0.57	-0.84	-1.11	-1.39	-1.66	-1.93	-2.20
100,000	-0.56	-0.83	-1.10	-1.37	-1.64	-1.92	-2.19	-2.46
Service Cost								

Figure 3.10: An illustrative picture of a part of the Excel sheet used in the thesis, showing some of Sens, presenting the costs for the turbines, with the cutoff prices marked in red and the values relative to goodwill

in Figure 3.11 below. In short, Project Information was used to collect data, Base Assumptions was used to present that data, Base Calculations was used to crunch the numbers, after which both ConsolidationFI and the Sens sheets were used to obtain the necessary information, in terms of making the important decisions regarding the projects.

After having taken a brief look at the materials and a more comprehensive overview of the methods used in the cost optimization of wind power plants, the thesis now moves on to presenting the actual Cost Structure Optimization of Wind Power plants using the methods, materials and other ways explained in detail before.

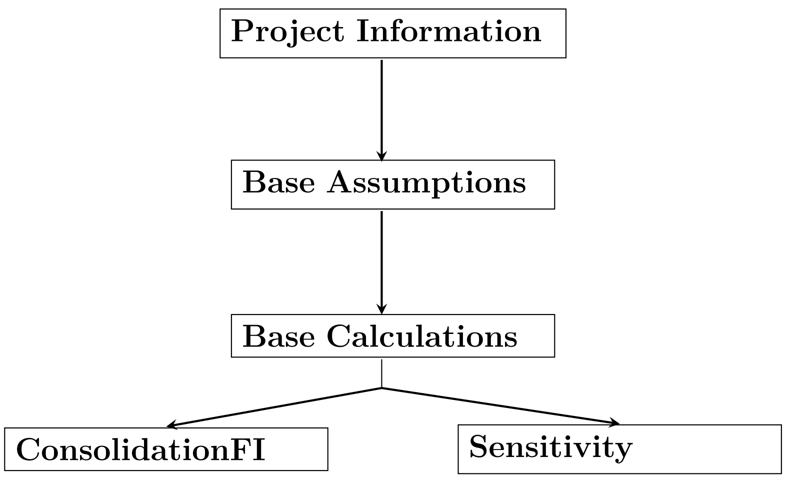


Figure 3.11: A block diagram of the Excel worksheet used in the thesis

4 The Cost Structure Optimization of Wind Power Plant Projects

The purpose of this master's thesis was, again, to prepare European Energy's bids for the upcoming renewable energy auctions, to be held later in 2018: this would mean that the projects would be ready in late 2019. The financial structure of a wind power plant project was examined in Chapter 2, and now the thesis moves on to the actual cost optimization of the aforementioned WPPs, with the identified components in mind.

As mentioned before, having a realistic pricing forecast was an integral part of the preparation, as it would tell the company two things: whether to try to get into an external support scheme such as a PPA or just sell directly to the grid. This would reveal the amount of profit the company could make for undertaking these projects. Having entered into a power purchase agreement while market prices are also competitive would handcuff the company to not getting the most competitive and cost effective price for the electricity produced. Additionally, as presented in Table 2.1, the bid was also dependent on the current price, as well as the size and the duration of the FiT/PPA. The current price used for this master's thesis was 31.5 €/MWh in 2017, while the average price of electricity in Finland for the first six months of 2017 has been around 32 €/MWh [20]. When adding the assumed 2 % annual price hike to that figure, the forecasted price for 2019, was 32.8 €/MWh. Wind power projects are assumed to have a lifetime of 25 years, so the calculations were made until 2044.

The pricing forecast, however, is not an easy task in an electricity market such as the Finnish one, as can be seen from Figure 4.1. Additionally, being in the Nordpool market also makes electricity prices in Finland at least partly dependent on the electricity production elsewhere: the amount of rainfall earlier in the year for instance enables more Swedish and Norwegian hydro power to enter the markets, which can potentially have a price-lowering effect.

There is also often a deficit in the Finnish energy production, which means that electricity has to be imported from elsewhere, possibly leading to higher prices. For instance as of June 2017, the average consumption so far in Finland has been 9882 MWh/h, while average production is at 7531 MWh/h [39].

A figure showing the electricity prices in Finland since 2003 can be seen in Figure 4.1 below. It should be noted, however, that the electricity prices in the current year of 2017 show only the first six months. This might mean that the price forecast or starting point of 31.5 €/MWh is a tad optimistic, and needs to be adjusted before the actual bid is made.

Figure 4.1 also shows a trend line in the prices of the electricity. While the trendline does indicate a downward motion, it should be noted that especially around 2010 the prices in Finland were extremely high (coincidentally, around the time of the previous feed-in premium was decided on, possibly explaining the size of the premium), which might make the use of such a trend line questionable in forecasting prices. Here it is presented purely as a point of interest. A professionally made pricing forecast by a company specializing in energy and electricity prices does, however, supported the downward trend somewhat. That company was employed and asked of their opinions in the current electricity prices in and where they might go in the future, and they came up with an estimate for the next 15 years. Their estimate, denoted here as Forecast, gave an estimate of the electricity prices in Finland, and predicted that the electricity price would go up to somewhere around 32.8 €/MWh by 2033, from their estimated electricity price of 25.8 €/MWh in 2019.

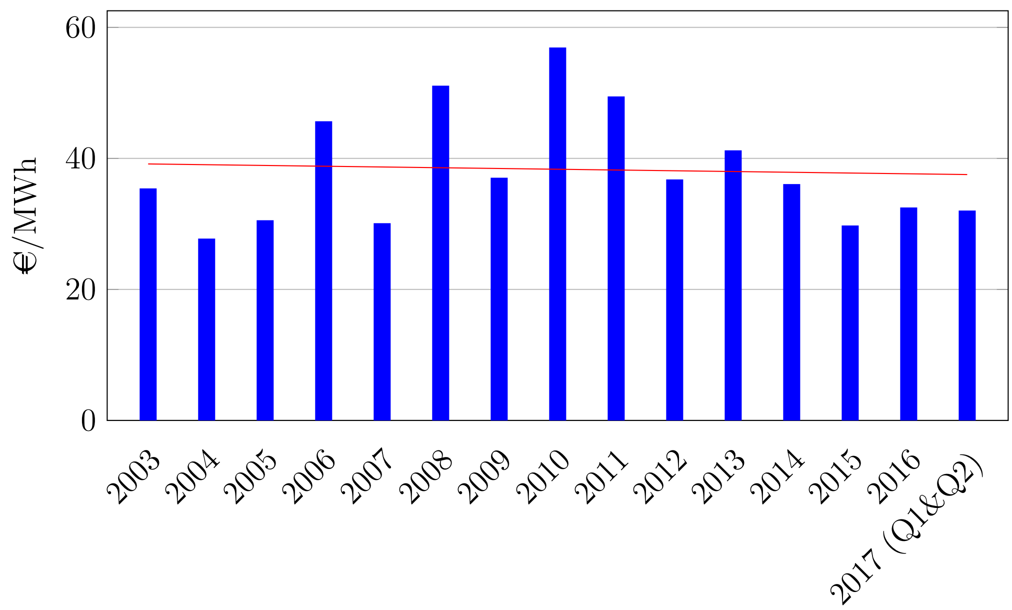


Figure 4.1: Electricity prices on average in Finland from 2003 to the first half of 2017, in addition to a trendline (in red) over the whole period, constructed from [20]

As a reference, the 2 % annual hike in electricity prices would be as follows: a 2 % yearly increase starting from 31.5 €/MWh in 2017 until 2033 would mean a price of approximately 43.2 €/MWh in 2033. This was a big deviation from the estimated price, and this was something to keep in mind while this thesis was being written: it was important to keep in mind all of the scenarios, and the scenarios with and without a feed-in tariff, although the latter would be of no significant interest, and would be presented on a nice to know- basis.

Table 4.1 shows a comparison of the different predictions as well as the assumed 2 % annual price increases in electricity prices. As can be seen from the table, price forecasts vary significantly, with the minimum being 40.2 €/MWh and the maximum being at 53.8 €/MWh in 2044; the end of the 25 years' lifetime starting from 2019. This did make predicting the prices very difficult, for reasons stated earlier. Electricity prices in Finland, according to Figure 4.1, do seem quite cyclical though, which might explain the differences in the predictions. Most likely the real price of electricity in Finland between 2019 and 2044 lies somewhere between these predictions.

Table 4.1: A table showing different forecasts of electricity price developments

	2033	2044
Forecast	32.8 €/MWh	40.2 €/MWh
Constant 2 %	43.2 €/MWh	53.8 €/MWh

Compromises between the expert's forecast and European Energy's estimate of an annual 2 % rise in prices could also be used: the expert's prediction until 2033, and then an annual 2 % rise in electricity prices. The prices are presented in Table 4.2 and Table 4.3, where Compromise A represents the experts' prediction in 2033 followed by a 2 % annual increase (amounting to an increase of around 1.85 % in total), and Compromise B represents a starting price of 32.6 in 2017, as per the experts' prediction, and 32.8 in 2033. This trend is then continued on to 2044, which equates to a tiny annual increase in prices of around 0.036 %.

Table 4.2: A table showing Compromise A as a future electricity price forecast

	2033 Prediction	2044 With a 2 % rise after 2033
Compromise A	32.8 €/MWh	40.8 €/MWh

Table 4.3: A table showing Compromise B as a future electricity price forecast

	2033 Prediction	2044
Compromise B	32.6 €/MWh	32.9 €/MWh

The different estimates or forecasts are, again, depicted in Figure 4.2, with Constant being the expected 2 % annual increase in electricity prices. As can be seen in Table 4.2 and Table 4.1 as well as Figure 4.2, the forecasts differ greatly, and the spread between the estimates is quite large, considering the fact that the FiT/PPA and market price will most likely be exceedingly close, and it is an actual consideration these days whether to get into a tariff system (or the auction price agreed upon) in Finland for a certain period of time or not, as the costs of wind energy have come down significantly over the past few years (and decades). A balancing act of many different pricing models and forecasts was vital to the success of this master's thesis, due to not only the fact that the estimates differ quite significantly, but also the importance of electricity prices to the cost optimization of the projects in question as well as wind power projects in general. This is why also compromises to the electricity prices were made, which were the middle ground between the two predictions. This seemed to be quite a good fit, since the annual increase in the electricity prices if following the experts' predictions further was close to 2 %: it was around 1.6 % from 2019 to 2033. Several compromises were made due to the fact that not only is it of importance to know the electricity price in 2044, but it is also vital to know how it got there, and with what type of annual increase or decrease: the annual increase in prices of around 0.036 % (or almost stagnant prices) was chosen as the absolute worst-case scenario.

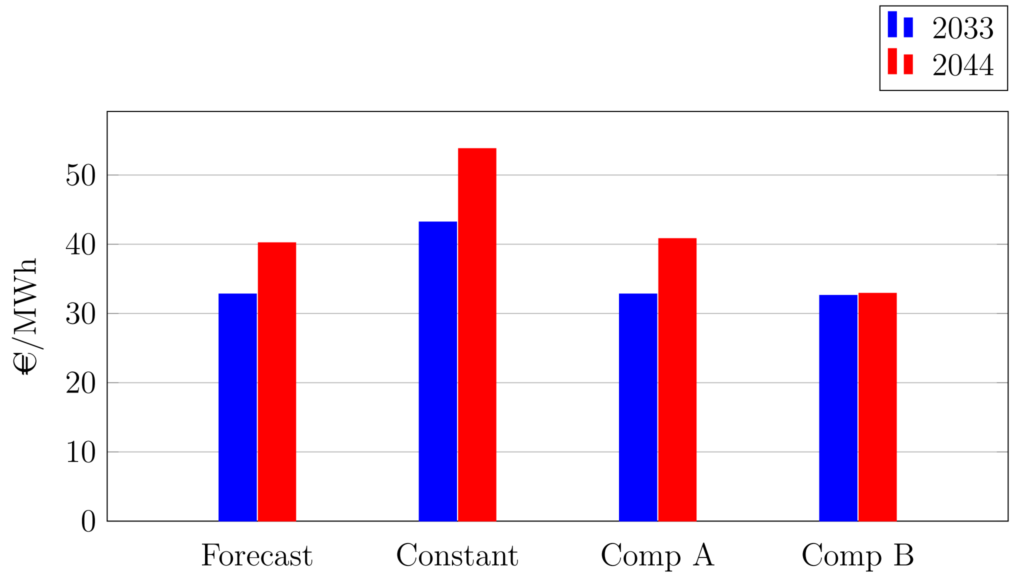


Figure 4.2: The pricing forecasts for the electricity price in Finland

Due to the similar outcome of Compromise A and Forecast (a 1.85 % and a 1.6 % annual price hike), only Compromise A, Constant and Compromise B were chosen as the predictions to proceed with, as presented in Figure 4.2: Compromise B takes the trend of Forecast and continues it on to 2044, Constant has a steady 2 % increase and Compromise A combines these two: Forecast until 2033, after which a 2 % increase is applied. In other words, the three different pricing scenarios chosen were as follows:

1. 32.8 €/MWh in 2019, with a 2 % annual increase in prices, referred to as **Scenario 1** from now on (Constant)

2. 25.8 €/MWh in 2019, with a 1.85 % annual increase in prices, referred to as **Scenario 2** from now on (Compromise A)

3. 32.6 €/MWh in 2017, with a 0.036 % annual increase in prices, referred to as **Scenario 3** from now on (Compromise B)

The different scenarios are presented in graph form in Figure 4.3. It was important to note here that the scenarios were not constructed in order to have a perfect forecast of the electricity prices in the future. Rather, the different scenarios were used to be able to cover as much ground as possible, and most likely the real electricity price development would fall somewhere between the predictions, as presented by the gray area between the curves in Figure 4.3.

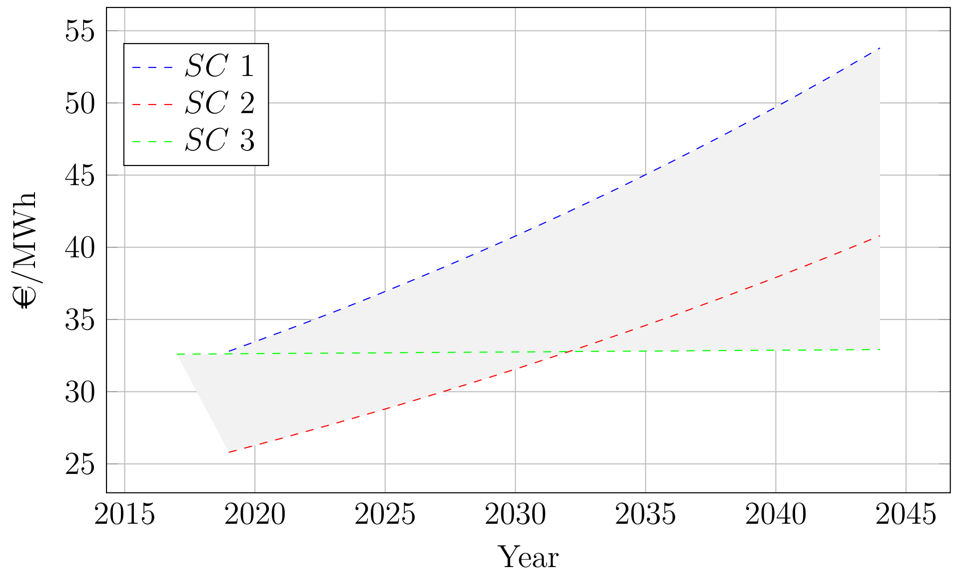


Figure 4.3: The different price forecasting scenarios, presented in graph form, as well as the probable range for the actual electricity prices, marked in gray

An additional metric that could be utilized to gain an understanding of the future price developments of electricity are national and EU targets for electricity prices. Pledges to decrease the amount of fossil fuels in the energy mix of the European Union, such as the aforementioned Paris agreement, are likely to decrease the amount of fossil fuels used in Europe, which might lead to an increase in electricity prices. An estimate of the future developments of energy prices in the European Union is presented in Figure 4.4 [40].

While it is difficult to get an exact figure of the electricity prices from Figure 4.4, it can be seen even with a bare eye that it is an upward trend. Not only is a hefty price increase in the EU a target, it is also the evaluation of some experts. This loans some credence to the, otherwise arbitrary, estimate of a 2 % annual rise in the electricity prices in Finland. It was deemed very possible that electricity prices would go up in the future, and that increase in prices might very well be close to 2 %. The question would be whether they would first go down in the near future: Forecast predicted a 2019 price of 25.8 €/MWh, while a constant 2 % price hike would mean a 2019 price of 32.8 €/MWh, like previously mentioned.

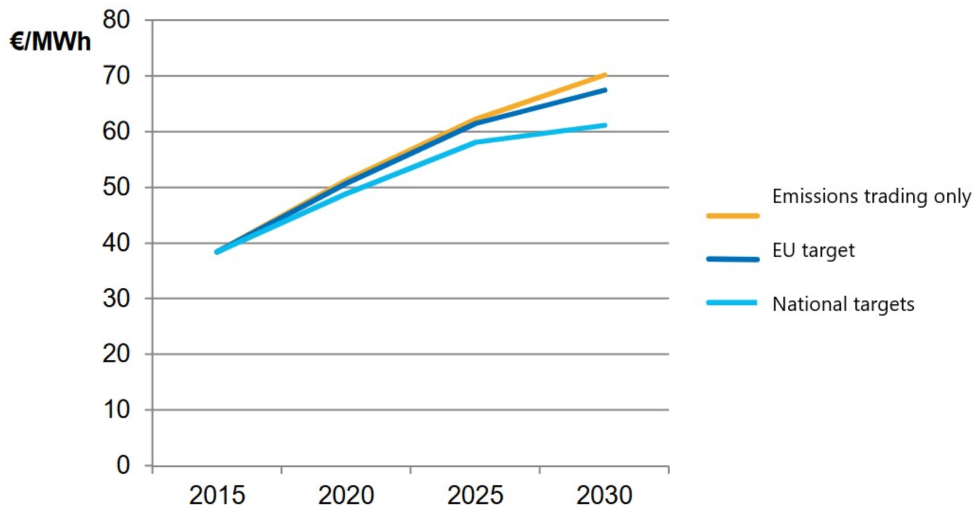


Figure 4.4: Estimates for energy prices in the EU for the next 15 years, translated from [40]

The market price of electricity and its changes in the future are not only an interest due to the fact that it is important to know whether a FiT/PPA scheme is viable for the duration of the tariff. It is also important to have an idea on the electricity prices since wind power plants have a lifetime longer than the (expected) tariff or purchase agreement duration. In other words, after the support scheme has ended, in for instance 15 years, the turbines will still produce electricity for at least 10 more years. Electricity produced then will be sold straight to the market: the market price has a financial impact in more ways than one when doing the planning for a WPP project.

It should be noted here again that a tariff and an auction system can be seen to be in direct contradiction to each other and mutually exclusive: there would be no point in having an auction system if the government then produces a support scheme to buy electricity at a certain price when expecting companies to offer producing electricity at another price. This is why the term PPA was used here alongside tariff/premium: if the auction bid is won at 55 €/MWh, then it would be the price at which electricity is sold at, regardless of market prices, similarly to a PPA. A premium system on the other hand, would have the electrity supplier receive their full price when market prices are above the reference price, and their full premium when market prices are below the reference price.

4.1 The Costs of Wind Power Projects

The main components of the COE of wind power plants were presented earlier in Chapter 2. This chapter introduces the same concepts, now for the project or projects in the real world, with actual offers and input from manufacturers and other contractrors, before moving on to inserting the received data and offers to the softwares presented earlier: WindPRO and Excel.

Offers were received from wind turbine manufacturers regarding many different aspects of their turbines. They are split into two parts in the next subchapter, in order to first gain an understanding of the power curves (and subsequently, the production) of the turbines, but also to present the different components of the Cost of Energy of wind power plants more clearly.

4.1.1 Offers from Wind Turbine Manufacturers

The offers received from Manufacturer A, Manufacturer B, Manufacturer C and Manufacturer D were not for specific sites, but a package for all the four sites. This was due to at least two reasons: it is of course beneficial for the manufacturers to try to sell as many of their turbines as possible and they would prefer to bundle them up. Another matter was that due to the different kinds of regulation in wind power markets, standard turbines might often be a specific type of fit: one size fits all somewhat, but fits no site perfectly. For instance, out of the four different offers acquired for the four different site projects in this master's thesis, only one type of the turbines had a tip height of 220 meters; one had a tip height of 200 m while two others were designed for 230 meters. Rules and regulations often differ in terms of proximity to housing or other buildings, maximum tip height of the turbines and so on. This makes it so that manufacturers sometimes offer site-specific turbines, to match the exact requirements of a site, which allows for the cost optimization of the power plant both in terms of profits and losses. For this to be possible, manufacturers often naturally prefer there to be several turbines, which also lowers the costs for the customer. For instance for projects in Finland, European Energy aimed for a tip (total) height of 220 meters, an unusual height that can not necessarily be applied to projects in other countries due to other kinds of specifications. Specifications may differ due to many different reasons, such as restrictions imposed by the aviation industry, as well as, in some cases, the military, as is sometimes the case for instance in Finland where these projects are located.

The offers from Manufacturers A, B, C and D initially came in two parts. First the power curves and the initial technical specifications (such as the acoustic measurements, not relevant to this master's thesis) were acquired: the production of the turbines at different wind speeds. All of the turbine types had rated powers of around 4 MW. These values were inserted into the Excel, to give a brief overview of the price range (and the service cost range) that would be viable for European Energy to be interested in the turbines. After that there was either a meeting with the manufacturer, or more specific information relating to said costs were acquired via e-mail. The initial part of the offers, the power curves, are presented below (for the Mustalamminmäki site, which was used to represent all the sites), as well as the initial Excel input data for the respective offers. It can be seen from Figure 3.10, for instance, that European Energy should not pay more than 90 000 € per year for the service cost, if the initial price of the turbine is 3.9 M€. The power curves of the respective initial offers from all the manufacturers are presented below.

The power curves, which were used as data for the WindPRO software, are all presented in one figure in Figure 4.9 below. WindPRO and the input data is presented

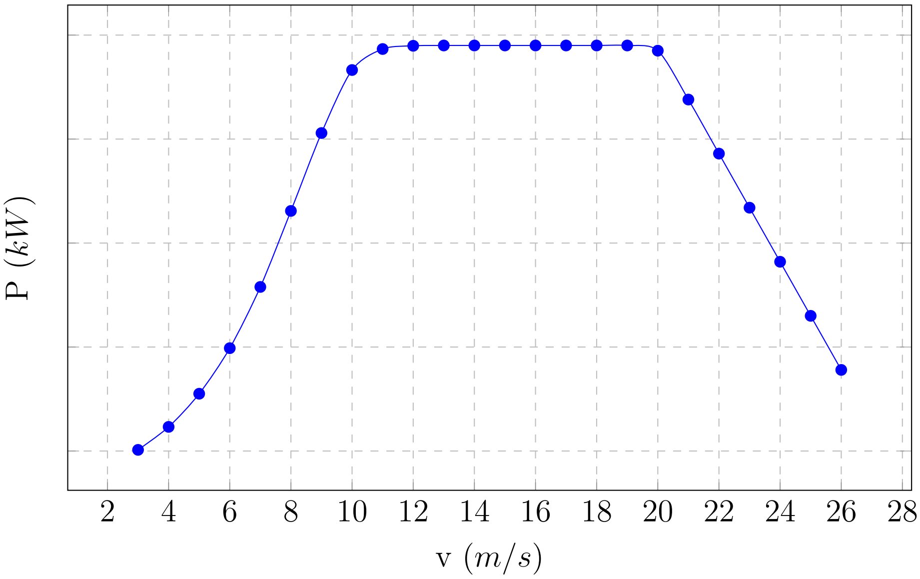


Figure 4.5: The power curve for manufacturer A's turbine

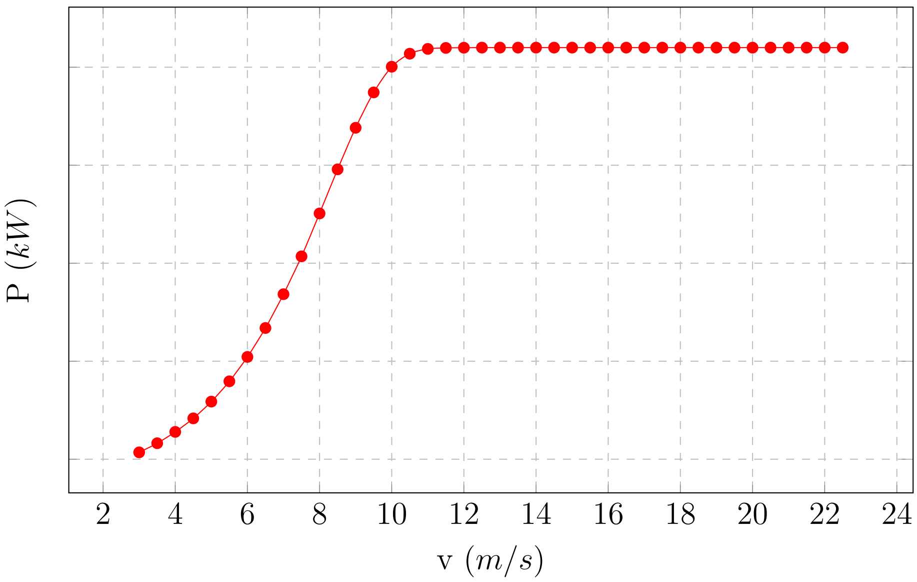


Figure 4.6: The power curve for manufacturer B's turbine

in more detail in Chapter 4.2. All the power curves assume an air density of 1.225 kg/m^3 and other standard conditions such as an undisturbed air flow, clean rotor blades, normal turbulence and normal *wind shear* (wind shear refers to a phenomenon where wind speed or direction changes between two points, such as the upper and lower parts of a wind turbine rotor).

Figure 4.9 presents the upsides and downsides of all the rotors quite accurately. It can be seen, for instance, that Manufacturer C's turbine ramps up to higher

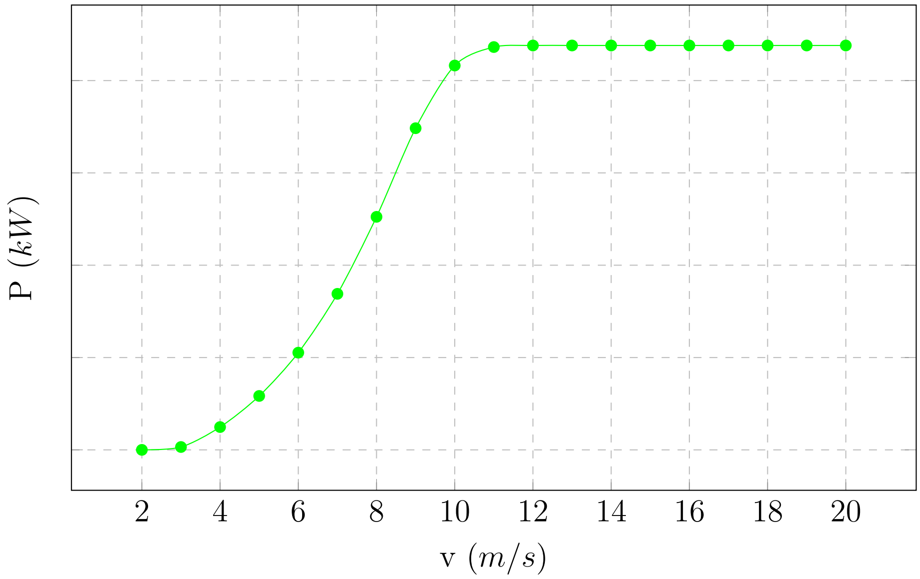


Figure 4.7: The power curve for manufacturer C's turbine

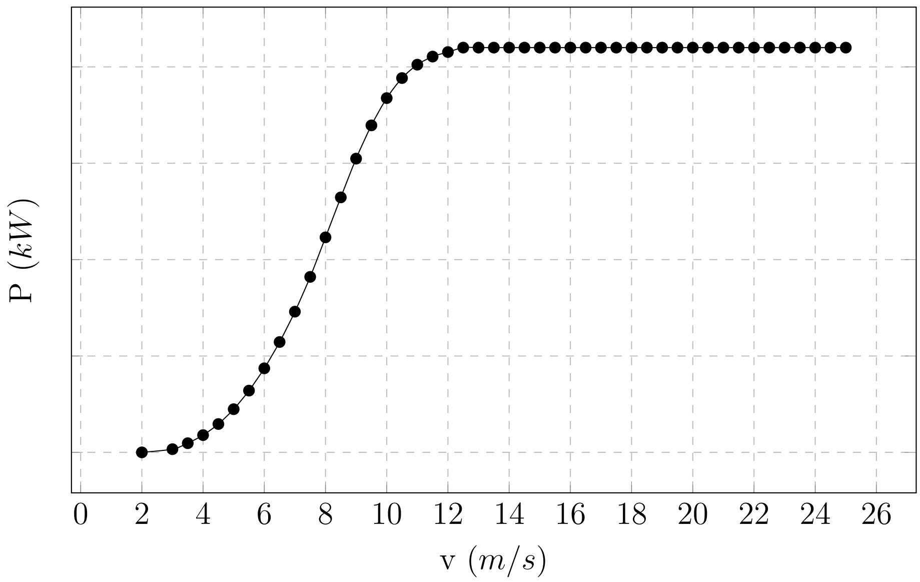


Figure 4.8: The power curve for manufacturer D's turbine

productions a little faster, but the production goes down at a lower speed than with Manufacturer D's corresponding turbine. This is a case where the energy roses from the WindPRO data are needed, to find out whether the cliff-edge phenomenon of the production at higher wind speeds is relevant, or whether wind speeds are expected to stay at such a low threshold that the added production of Manufacturer D's turbine at higher wind speeds is irrelevant. Turbine B does offer productions at higher wind speeds and has a later cutoff point than C, while A also produces somewhat after

C's cutoff speed of around 20 m/s. All in all, the power curves showed that the turbine types were suitable for different conditions, with Manufacturer B's offer being the one in the middle, and C and A having significant upsides and downsides, and D being a notch below B and C. If most of the energy produced is at lower wind speeds, solutions C and B seemed to have an edge over the other two when looking at nothing but production.

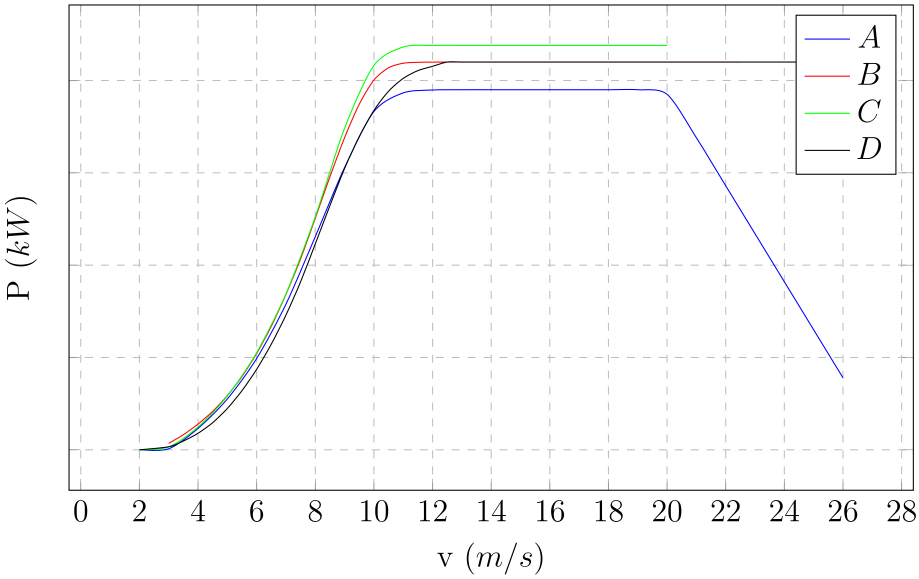


Figure 4.9: The power curves of all the turbines under consideration illustrated in one figure: Turbine A in blue, Turbine B in red, Turbine C in green and Turbine D in black

Another important part of the consideration that went into initially determining the attractiveness of the offers was the tip height of the turbines. It was believed that the restriction on the sites, 220 meters, was quite final and therefore higher tip heights were not under consideration. A lot of the offers received were for unoptimal heights, either under or over the 220 meters, which provoked proposing site-specific turbines for all the sites, a total of 24 turbines for all four sites. But if the sites did suddenly permit towers higher than 220 meters, it is somewhat straightforward to change the production values as well as adjust the cost of the turbines and the service costs that they require.

There was, naturally, also the issue of pricing, which was, barring an incredibly high difference in the productions of the turbines, still one of the more important (if not the most important) aspects of choosing the right tool for the job. Determining a suitable price range was done in Chapter 4.3. As stated before, the costs are the cost of the turbine as well as the cost of service, including things such as O&M costs.

4.1.2 Foundation, Grid Connection, Logistics and Road Costs

An integral part of the offers, which was not visible in either turbine or service costs or the power curve of the manufacturer's turbine, was the tower and the subsequent foundation of the tower. Generally, after checking that the soil at the actual site is of sufficient quality to ensure that the foundations can be dug without extensive problems (which was done by travelling to the sites in Finland) the issue of the towers is raised. While, as can be seen in Figure 2.1, the turbine does often equate to up to 75 % of the total costs, the foundation is also a critical part, due to two things. Firstly, the foundation itself, and the costs of the foundation. Secondly, different foundations might affect for instance the need for road construction and storage space greatly. Several different types of foundation exist for wind turbine projects. These include spread foundation, where a big plate is placed on the ground to more evenly distribute the weight of the tower. Soil stabilization refers to a process where the soil can be strengthened to be able to hold the WTG by adjusting the properties of the soil such as the stiffness, homogeneity and permeability. Piled foundation on the other hand is a process in which the soil is strong enough on itself to hold the tower, and planting piles into the ground helps distribute the weight of the towers more efficiently. [41]

Steel towers are often easier to transport to the site, and the foundation is relatively simple to do. As they are relatively easy to transport and little storage space is needed, they place little additional strain on the road construction and other miscellaneous costs. Hybrid towers, on the other hand, not only cost more straight up, but also require more storage space, and additional logistical requirements for the cement trucks. Hybrid towers, as opposed to steel towers, are a combination of steel and concrete, with varying shares of both. [41]

Out of the offers here, Manufacturer A could only offer a hybrid tower, while Manfacturer B promised to deliver a steel tower, as did Manufacturers C and D. Due to the reasons stated above, it is no wonder that the offers with the steel towers were, in this case, significantly more attractive. The tower was, in short, not the only thing to be considered, but it is more important than what the cost figures in Figure 2.1 might initially make one think.

Being able to deliver turbines with a certain price tag and a low service cost while having high production was naturally important. In addition to this, the type of tower can often tip the scales in the favor of one offer over another. A part not yet discussed in this master's thesis that still has an impact was the delivery. A lot of the turbines here, offered by Manufacturer A, Manufacturer B, Manufacturer C and Manufacturer D, were newer versions, sometimes nothing more but prototypes at this stage. This was due to the high degree of competition in the field as well as the rapid advancement in technology in wind turbines. Delivery times for the turbine were hence important, even though the actual times (provided that EE wins the auction) to building the wind turbine power plants were still relatively unclear. This was due to the nature of wind power plant construction: a lot of different authorities are involved in the process of acquiring permits and licenses, and timetables are often difficult to make. An estimate by European Energy for construction was no earlier than late 2018.

Manufacturer B talked about a delivery schedule of during or after Q2/2019. Manufacturer C promised a delivery schedule of "within 2019", while Manufacturer D guaranteed a start of production in June of 2018 and a delivery of within the third quarter of 2018. Manufacturer A was unsure of their delivery schedule.

An offer was received from a company that would provide the roads, grid connection and other logistical work, and it was divided into several parts, depending on the requirements as well as the specific sites. The offers for all the sites (even though only Mustalamminmäki is used here) were as presented in Table 4.4:

Table 4.4: A table presenting the offers for the construction costs of the different sites

Site	***Price per WTG***
Koiramäki	302 500 €
Mustalamminmäki	**268 750 €**
Ahvenneva	300 000 €
Honkakangas	320 000 €

Mustalamminmäki, the bolded part, was, as mentioned before, used to represent all the sites. Due to this, it was important to keep in mind the figures presented in Table 4.4, since the costs for Mustalamminmäki were a tad lower than that of the others, and keeping this in mind would prevent any unwelcome surprises when eventually looking at the detailed figures for all the sites. Other information received included things such as cable costs: the AHXAMK-W 3x300+35 would cost around 30 €/m, with a length requirement in total for Mustalamminmäki of around 13 kilometers.

4.2 WindPRO Data

After obtaining the offers from Manufacturer A, Manufacturer B, Manufacturer C and Manufacturer D, including the power curves of their respective turbines, the data could be put into the WindPRO software to get a rough estimate of the production figures of the different sites. While the tip height of the projects under consideration currently would most likely be 220 meters, it might also have been useful to know wind production data from a little further and after said point, to be able to compare it with the production at 220 m. This is due to the fact that while higher wind turbine power plants often produce more electricity, they also cost substantially more. It might also have been be worthwhile to know the production at, say 230 meters, in case the production wass a lot higher and the building permit might possibly be altered to allow towers of a height of 230 m. This happens every so often, due to the long nature of wind power plant projects. Often the initial inquiries and paperwork is done several years before the start of the actual construction of the site, and during this time either policies that the area originally had might have changed or they might be swayed by the additional production of a higher tip height (and therefore higher production) of a WPP. This is often not a last-minute change, though, since altering the building permit may be a lengthy process too.

This master's thesis was a preparation for the auction of four different WPP sites, all of which had four different considerations in terms of the actual manufacturer of the turbines, and three different scenarios: this is why only one of the sites was chosen to represent them all. Nevertheless, even this choice meant 12 different cases. The WindPRO data and simulations did support this approach, since it showed that the sites were in many ways very similar. The sites were located very close to each other geographically, and one type of turbine fairing well at one of the sites was often taken as a sign of it doing well in all of the sites due to the proximity of the sites. In order to save space, this chapter only illustrates the relevant WindPRO data for one site, Mustalamminmäki. In addition to the close geographical proximity of the sites being used in production estimates, at times during the making of this master's thesis it was beneficial to look at the projects as one big project due to the possible negotiating power than 24 turbines might add. An order of 24 turbines would likely result in an order of around 60-100 million euros: this made it possible to use the projects as leverage in price negotiations.

When following the steps explained earlier, the WindPRO software yielded results as presented below. Figure 4.10 represents a part of the data that WindPRO produced for the WPP site in Mustalamminmäki with Manufacturer A's turbine. As can be seen from the figure, Manufacturer A's turbine has a total yield (net) of around 121.8 MWh per year, with a mean wind speed of 7.3 m/s^2, and a capacity factor of 44.5 %. The tip height of Manufacturer A's offer was only 200 meters, though.

Calculated Annual Energy for Wind Farm

				Specific results¤)			
WTG combination	Result PARK [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Park efficiency [%]	Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	121.812,8	131.764,4	92,4	44,5	15.226,6	3.904	7,3

¤) Based on wake reduced results, but no other losses included

Calculated Annual Energy for each of 8 new WTGs with total rated power

	WTG type						Power curve		Annual Energy	Park		
Links	Valid	Manufact.	Type-generator	Power, rated	Rotor diameter [m]	Hub height [m]	Creator	Name	Result [MWh]	Efficiency [%]	Capacity factor [%]	Free mean wind speed [m/s]
1 A	No				142,0	129,0	USER	Mode 0, Rev. 0	15.485,7	93,73	45,3	7,28
2 A	No				142,0	129,0	USER	Mode 0, Rev. 0	14.752,5	89,65	43,2	7,26
3 A	No				142,0	129,0	USER	Mode 0, Rev. 0	14.590,2	88,81	42,7	7,26
4 A	No				142,0	129,0	USER	Mode 0, Rev. 0	14.924,8	91,29	43,7	7,24
5 A	No				142,0	129,0	USER	Mode 0, Rev. 0	15.531,2	94,36	45,4	7,27
6 A	No				142,0	129,0	USER	Mode 0, Rev. 0	15.551,3	94,39	45,5	7,27
7 A	No				142,0	129,0	USER	Mode 0, Rev. 0	15.102,4	91,08	44,2	7,30
8 A	No				142,0	129,0	USER	Mode 0, Rev. 0	15.874,6	96,27	46,4	7,27

Figure 4.10: WindPRO data figure A for Mustalamminmäki

Figure 4.11 represents a part of the data that WindPRO produced for the WPP site in Mustalamminmäki with Manufacturer B's turbine. Figure 4.11 reveals that

Manufacturer B's proposal had yields that were a little higher than with Manufacturer A's respective offer, with a total net yield of around 140.5 MWh per year, a capacity factor of just over 50 %, and with a mean wind speed at hub height of 7.5 m/s^2. It should be noted, however, that Turbine B had a tip height of 230 meters, and if this offer was chosen, it would have to be site-specific turbines, adjusted to the requirement of 220 m.

Calculated Annual Energy for Wind Farm

				Specific results¤)			
WTG combination	Result PARK [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Park efficiency [%]	Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	140.487,9	151.413,5	92,8	50,1	17.561,0	4.390	7,5

¤) Based on wake reduced results, but no other losses included

Calculated Annual Energy for each of 8 new WTGs with total MW rated power

	WTG type						Power curve		Annual Energy	Park		
Links	Valid	Manufact.	Type-generator	Power, rated	Rotor diameter [m]	Hub height [m]	Creator	Name	Result [MWh]	Efficiency [%]	Capacity factor [%]	Free mean wind speed [m/s]
1 A	No				150,0	145,0	USER	Mode PO1	17.834,8	93,95	50,9	7,56
2 A	No				150,0	145,0	USER	Mode PO1	17.076,1	90,27	48,7	7,54
3 A	No				150,0	145,0	USER	Mode PO1	16.859,5	89,30	48,1	7,53
4 A	No				150,0	145,0	USER	Mode PO1	17.251,7	91,76	49,2	7,51
5 A	No				150,0	145,0	USER	Mode PO1	17.868,8	94,51	51,0	7,54
6 A	No				150,0	145,0	USER	Mode PO1	17.909,4	94,63	51,1	7,55
7 A	No				150,0	145,0	USER	Mode PO1	17.427,3	91,49	49,7	7,58
8 A	No				150,0	145,0	USER	Mode PO1	18.260,2	96,34	52,1	7,55

Figure 4.11: WindPRO data figure B for Mustalamminmäki

Figure 4.12 represents a part of the WindPRO data produced for Mustalamminmäki with Manufacturer C's turbine. Manufacturer C's turbine had the best prodution figures of all the turbines: an annual production of over 144 MWh, a mean wind speed of 7.5 m/s^2 and a capacity factor of 47 %, and a total height of 220 meters. According to the production numbers alone, Turbine type C was a very strong contender. Similarly to B, though, C had a tip height of 230 m, and site-specific turbines would again be needed if this offer was chosen.

Figure 4.13 represents a part of the WindPRO data produced for Mustalamminmäki with Manufacturer D's turbine: the annual production was at a little over 128 MWh, CF just below 44 %, mean wind speed 7.6 m/s and tip height 220 m. While Manufacturer D's power curve looked promising, the overall production estimate of Manufacturer D's turbine was the second worst of the bunch. Although production was not the only criteria being looked at while trying to optimize the cost structure of the power plants going into the auction, Manufacturer A's turbine seemed like the least optimal choice, while both Manufacturer B's and Manufacturer C's turbines looked very promising.

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Park efficiency [%]	Specific results¤) Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	144.419,9	155.445,2	92,9	47,0	18.052,5	4.122	7,5

¤) Based on wake reduced results, but no other losses included

Calculated Annual Energy for each of 8 new WTGs with total rated power

Links	WTG type Valid	Manufact.	Type-generator	Power, rated	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Result [MWh]	Park Efficiency [%]	Capacity factor [%]	Free mean wind speed [m/s]
1 A	No				150,0	145,0	USER	Rev. 01	18.336,1	94,08	47,8	7,56
2 A	No				150,0	145,0	USER	Rev. 01	17.546,5	90,35	45,7	7,54
3 A	No				150,0	145,0	USER	Rev. 01	17.333,0	89,43	45,1	7,53
4 A	No				150,0	145,0	USER	Rev. 01	17.735,0	91,89	46,2	7,51
5 A	No				150,0	145,0	USER	Rev. 01	18.373,7	94,66	47,9	7,54
6 A	No				150,0	145,0	USER	Rev. 01	18.405,4	94,73	47,9	7,55
7 A	No				150,0	145,0	USER	Rev. 01	17.921,1	91,63	46,7	7,58
8 A	No				150,0	145,0	USER	Rev. 01	18.769,0	96,47	48,9	7,55

Figure 4.12: WindPRO data figure C for Mustalamminmäki

Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Park efficiency [%]	Specific results¤) Capacity factor [%]	Mean WTG result [MWh/y]	Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	128.428,2	139.318,3	92,2	43,6	16.053,5	3.822	7,6

¤) Based on wake reduced results, but no other losses included

Calculated Annual Energy for each of 8 new WTGs with total rated power

Links	WTG type Valid	Manufact.	Type-generator	Power, rated	Rotor diameter [m]	Hub height [m]	Power curve Creator	Name	Annual Energy Result [MWh]	Park Efficiency [%]	Capacity factor [%]	Free mean wind speed [m/s]
1 A	No				148,0	146,0	USER	Version 1.0	16.338,6	93,51	44,4	7,58
2 A	No				148,0	146,0	USER	Version 1.0	15.544,7	89,31	42,2	7,56
3 A	No				148,0	146,0	USER	Version 1.0	15.348,8	88,37	41,7	7,55
4 A	No				148,0	146,0	USER	Version 1.0	15.725,5	90,95	42,7	7,53
5 A	No				148,0	146,0	USER	Version 1.0	16.380,7	94,17	44,5	7,56
6 A	No				148,0	146,0	USER	Version 1.0	16.404,0	94,20	44,6	7,57
7 A	No				148,0	146,0	USER	Version 1.0	15.921,0	90,79	43,2	7,59
8 A	No				148,0	146,0	USER	Version 1.0	16.765,0	96,16	45,5	7,57

Figure 4.13: WindPRO data figure D for Mustalamminmäki

After aqcuiring the initial data (the power curves), using that data in combination with the SODAR measurement data as well as other information about the projects and then using WindPRO to get initial estimates of production, the best one could now be chosen in terms of production. As mentioned before, the Sensitivity sheet on the Excel file provided (as represented in Figure 3.10) was also used to determine the price range, both in terms of service costs as well as the actual price of the turbines. The Excel sheet is presented more thoroughly in Chapter 4.3. As briefly mentioned before, if the turbine type was to be chosen according to nothing but the production, Manufacturer C's turbine with an annual electricity production estimate of more than 144 MWh was the strongest contender.

4.3 Excel Analysis

Excel was used in order to make the official assessments of the feasibility of the projects, as well as the actual cost optimization of the power plants as Excel allowed easy manipulation of the data with visible effects. Excel was also used in a preliminary phase to estimate the feasibility of the offers from Manufacturers A, B, C and Manufacturer D. As presented in Figure 2.1, not only does the cost of the turbine possibly make a difference, but other factors are also key such as foundation and electric installation. Different manufacturers and different turbines may have different requirements for the foundations, which might increase costs. A thing to keep in mind was also that some turbines might initially seem cheap, but their costs are masked elsewhere: manufacturers might deliberately come out with a new, cheaper turbine, but one that has a higher operational and service cost, which would make up for the cheaper initial investment for the manufacturer. Still, as mentioned, Excel was initially used to determine the possible feasible price range for the different turbines, after which it was used more thoroughly, combining data from the WindPRO analysis, offers from the manufacturers as well as other information.

Taking into account the WindPRO data earlier as well as the initial specifications of the offers, Manufacturer A's turbine was ruled out due to the tip height being too low (200 m, as mentioned), which lead to an unoptimized production, as well as their inferior tower type and delivery schedule issues. Foundation and tower type, as specified in Chapter 4.1.2, was also an inferior choice for Turbine Type A.

4.3.1 Identifying the Crucial Parts for the Auction Bid

The purpose of this chapter was to finalize the components of COE in the projects to be undertaken by European Energy, which would be the most important aspect in the upcoming auctions: the cost of energy, added with the profit margin of the company's choosing, would determine the bid that European Energy would make in the upcoming auctions for renewable energy projects.

As stated and presented numerous times before, one of the most crucial components when optimizing the cost structure of a wind power plant were the profits it generates: in other words, the cost of energy. The profit, as also stated previously, was dependent on many different things. As has been presented, the profits were dependent on the production estimates of wind energy, as well as the estimates and predictions of current and future prices for electricity. An additional thing that could be seen from the figures presented was the impact and meaning of not only the prices of the turbines, but of the service costs of the turbines as well. For instance, as presented in Figure 3.10, the projects would achieve the profit requirements for 90 k€/year and a turbine cost of 3.3 M€, but if the cost of the turbine was 4.0 M€, a service cost of 70 k€ a year would be too much. Furthermore, the base service costs were found to be at an acceptable level, while the variable service costs, paid of the production with which wind turbine generation exceeds 30 %, were found to be too high. In other words, an aspect to optimize was found to be not only turbine and base service cost, but also the variable service cost of a turbine. This would be an important aspect for wind turbine projects in the future too, assuming that the production and capacity factor of WPPs continues to increase. In European Energy's previous projects in Finland, a WTG price of around 3.6 M€ and a service cost of around 80 k€ have been common.

Naturally, and as presented in Chapter 3, there were many other things to consider and add to the final calculations in addition to the things presented earlier in this chapter. The CAPEX and OPEX presented in Chapter 3.2.2 included a lot of other factors not yet discussed in great detail, that also have an impact on the cost structure of wind power plants. A lot of these figures were case-specific and might apply and be a major in other projects, while being insignificant or irrelevant in others. For instance, the CAPEX section of the Project Information sheet in the Excel file included costs for purchasing the land and neighbouring lands in order to build a wind power plant, while most often the land is leased from the owner and neighbours might be compensated, but their lands would not need to be purchased. The most important aspects relating to the cost structure of wind power plants could be identified for instance by manipulating the values in the Project Information sheet of the Excel and then checking the possible change in the Enterprise value on the Sensitivity sheet.

Most of the factors introduced in the OPEX and CAPEX in Chapter 3.2.2 were insignificant, even when they were taken into account or they did in fact apply for this project (as mentioned before, some are very case sensitive, and might only apply for specific projects). For instance, an estimate of the technical, legal and financial fees were made based on previous experience of European Energy's projects. Even if these estimates were doubled, the impact on the enterprise value would still be insignificant. A lot of values could be dismissed due to the fact that the Enterprise value was in dozens of millions, and some of the costs were one-time payments in the thousands: they had little to no significance to the end result. Therefore, they were dismissed as background noise in the optimization process and the most crucial aspects were identified.

The Excel, as explained before, allowed easy manipulation of the figures in order to try to figure out the most crucial cost components of a wind power plant project. Changing the values one at a time and then looking at the profit of the project gave a comprehensive understanding of the most important parts, and the parts that have the most influence on the bottom line. The results could be compared as a number relative to the initial profit margin or goodwill, denoted here as n_{Gw}.

The most critical values would be those that affect the profit margin the most. For instance, a slight increase in turbine prices would have a huge impact on the profit margins of the project. The dependency between the profit margin and the individual cost component of the project could be determined easily with a sensitivity analysis done in the Excel file, using for instance the Goal Seek function of Excel, as presented in Figures 4.14 and 4.15 below.

The values in the OPEX and CAPEX were manipulated as presented in Figures 4.14 and 4.15 and the results were as follows:

Looking at the information provided, it could be concluded that for these particular projects at least, the most important cost components in the cost of energy that can be impacted at the development phase of the process were turbine prices,

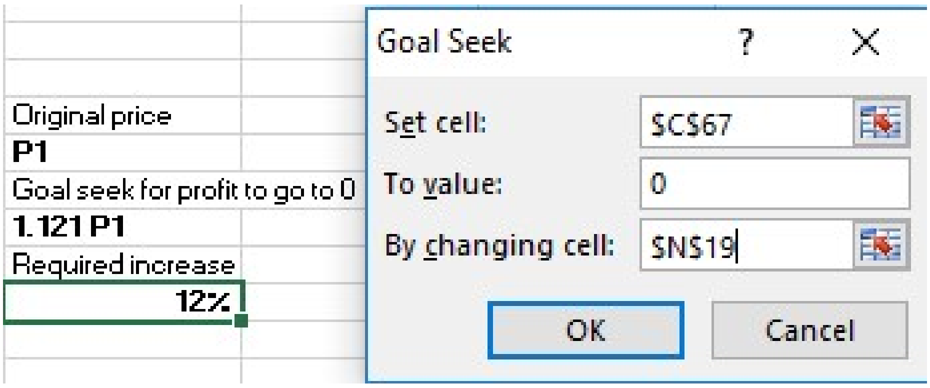


Figure 4.14: Goal seek and sensitivity analysis in the Excel file to figure out the most crucial cost components

	Variable	Current cell	Stress (+/–)	Impact, absolute value
1	Feed-in-tariff duration period (or PPA)	C24	-10%	1.26
2	FiT/PPA Size	FiT_Price	-10%	5.09
3	Land lease, EUR/WTG	'Base Assumptic	-10%	0.37
4	Gross production	'Base Assumptic	-10%	2.03
5	WTG price	C7	10%	2.79
6	Grid connection	'Project informat	-10%	0.30
7	Foundation & Construction	'Project informat	-10%	0.43
8	Balance costs	'Project informat	-10%	0.25
9	Grid usage fee (per MWh)	'Project informat	-10%	0.16
10	Grid usage fee (absolute)	'Project informat	10%	0.02
11	Bank fees	'Project informat	-10%	0.08
12	Development costs	'Project informat	-10%	0.13
13	EPC Project management	'Project informat	-10%	0.02
14	Other costs	'Project informat	-10%	0.07
15	Handling fee	'Project informat	-10.0%	0.03
16	Own power consumption	'Project informat	-10.0%	0.04
17	Technical surveillance	'Project informat	-10.0%	0.06
18	Uncertainty (standard deviation)	'Base Assumptic	-20.0%	-
19	O&M change	G10	10%	0.46
20	Interest rate of debt	C45	-0.1%	0.27
21	Power price indexation	C22	-1.0%	1.14
22	Service cost, variable	'Project informat	-1.0%	0.07
23	Corporate tax rate	'Project informat	-5.0%	-
24	Total losses	'Project informat	-1.0%	0.55
25	Insurance	'Project informat	10%	0.08
	Purchase of land & neighbouring real estate			

Figure 4.15: Sensitivity analysis performed in the Excel files in order to find the most crucial cost components of these projects, with WTG prices as the component

power price indexation forecasts, base service cost, foundation & construction, grid connection as well as the interest rate of debt. Other components would also have an impact, but their optimization would be more of a fine-tuning process and their impact would be relatively small.

1. Feed-in tariff or **Power Purchase Agreement size**
2. **Turbine prices**
3. **Feed-in tariff or Power Purchase Agreement duration**
4. Gross production

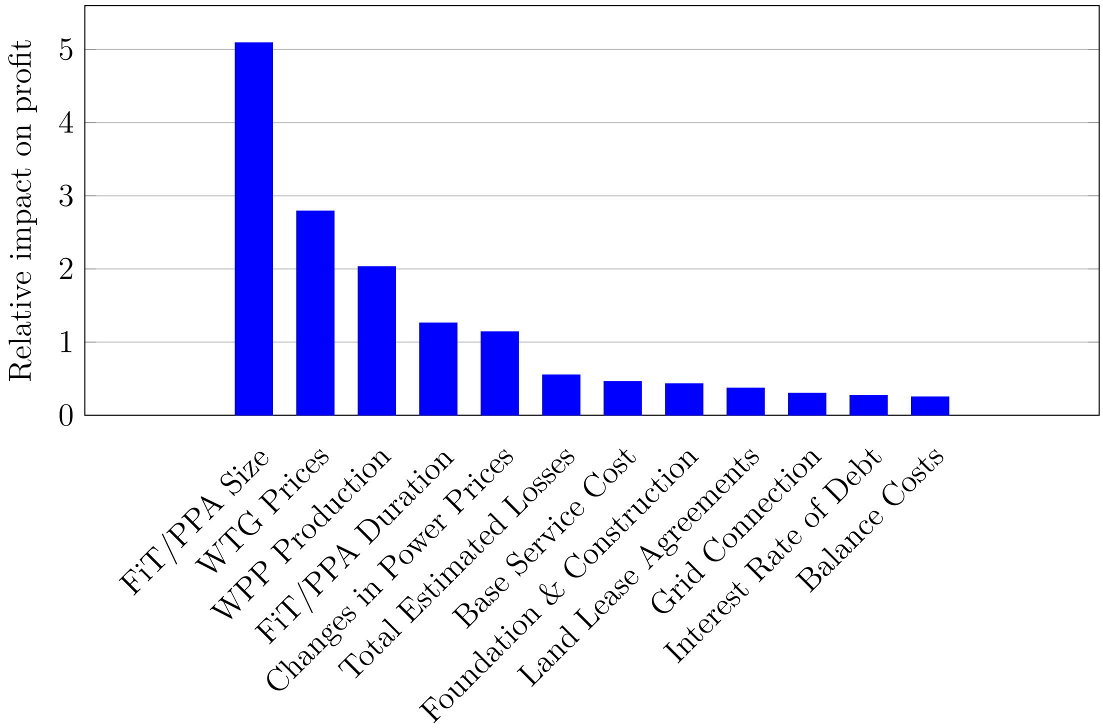


Figure 4.16: The cost structure of the projects under consideration, showing the most impactful cost components

5. **Total losses** (some parts, such as **Wake loss**)
6. The change in power prices
7. **Operations & Management/Service agreement costs, base cost**
8. **Construction and foundation costs**
9. **Cost of renting the land**
10. **Grid connection costs**
11. Interest rate of debt
12. Balance costs

While other, less significant components included things such as:

- Grid Usage fee (per MWh) and absolute
- Development costs
- Bank fees
- Other costs

- Technical surveillance
- Own power consumption
- Handling fee
- EPC Project management
- Corporate tax rate
- The purchase of land and neighbouring real estate as well as purchasing project rights might be a big factor in some projects, but they are very case sensitive and only apply to some projects
- Variable service cost, often dependent on production
- Uncertainty costs can also vary greatly between projects

The bolded parts were components that could still be influenced by price or cost optimization (or at least planned in a certain way), while things such as the gross production of the WPPs could be maximized, but after that there was little that could be done to increase the production.The main components for the cost of energy for wind power plants are also presented here. As briefly mentioned before, though, one way to increase for instance production, would be to increase the height of the towers and therefore (hopefully) increase wind speed, but that was beyond the scope of this thesis.

It should also be noted that the additional cost components that might not often be relevant, such as the acquisition of the real estate and neighbouring lands, would then also work to decrease other costs, such as land rent. The bolded parts were also the ones affecting the COE of wind power, and therefore, ultimately the auction bid. Additionally, it should be noted that the list provided in Figure 2.1, although from the year 2009 and the industry has undergone a lot of changes since then, was still quite accurate and the literature research supported the findings of this thesis, at least in the applicable parts. With the whole cost structure, however, there were also other parts to be taken into account when making calculations for the whole power plant. Additionally, price indexation for the different projects might also play a role in the cost structure of a wind power plant project, but that factor varies quite a bit, and the importance of the price indexation is relative to its size: a big price indexation (either positive or negative) has a higher impact on the prices than a smaller number.

Another thing to note was that it was important to take into account different turbines with the different cost structures, since the turbines had different production figures and therefore different income structures too. The order of importance of the different components changed little, although the magnitude of their importance could change. This meant that while the most important cost components stayed the same, their impact and magnitude of importance varied across the different turbines and projects.

This reinforced the importance of the notion of working on several scenarios at a time. The different scenarios, all with different pricing forecasts, had similar numbers otherwise in terms of cost component sensitivity, but they varied in terms of the importance of the duration of the FiT/PPA as well as the importance of power price indexation. This meant that some cost components and sensitivities would be different in different scenarios, due to the different base assumptions that the scenarios operated upon. The sensitivities presented in Figure 4.16 were average values of all the three different scenarios and three different turbine manufacturers' models that were still under consideration.

Additionally, it was important to notice here that while the results were applicable to projects undertaken by European Energy, certain things were bundled up (such as construction and foundation work) into one part of the project, and other project developers might keep them separate. This reduced the importance of the overall results somewhat and their applicability to other projects outside of the company, but the results should still be generally applicable to all wind power plant projects. The thesis now moves on to presenting the final stages of the offers from the wind turbine manufacturers as well as using the above information in optimizing and finalizing the auction bid.

4.3.2 Optimizing the Crucial Parts for the Auction Bid

With the initial knowledge of the turbine prices as well as the most crucial cost components of a wind power plant project in mind the rest of the turbine costs could then be negotiated. Out of the three possibilities still remaining, Manufacturer B was the first to respond. The actual initial offers are presented in Figures 4.17, which presents the turbine costs, and Figure 4.18, which depicts the average of the service costs for the turbines, below. It should be noted that service costs for Turbine B are in two parts: the base service cost as well as a variable service cost, which is usually paid on top based on the capacity factor. This variable cost is 0 with a capacity factor of 0.3, and is paid for the production by which capacity factor exceeds 30 % or 11 038 MWh, or another figure set by the manufacturer. With a capacity factor of 50.1 % and a total production of around 140 488 MWh/a for 8 turbines and therefore around 17 561 MWh/a for a single turbine,

$$17561\ MWh/a - 11038\ MWh/a = 6525\ MWh/a,$$

and with the variable service fee cost that Manufacturer B proposed, this would mean an additional cost of around 50 % more for Manufacturer B's turbine. It was worth noting that without this variable service fee, Manufacturer B's service cost would have been around the same as Manufacturer C's and Manufacturer D's, as can be seen in Figure 4.18.

Manufacturer B's offer was inserted into the Excel sheets and deemed slightly too high for the projects under consideration here. Here two important conclusions could be made: either the service price would need to decrease quite drastically, or the turbine price would need to decrease somewhat, or they would both need to go

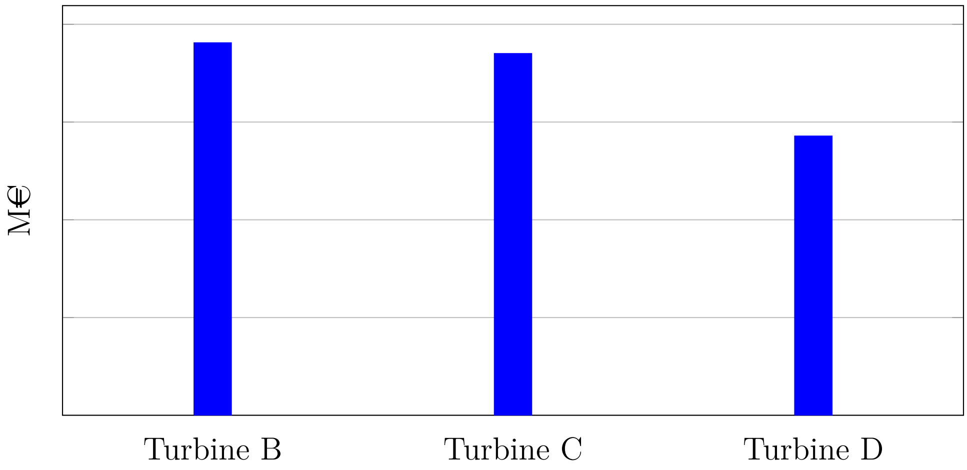


Figure 4.17: The prices received for the different turbines

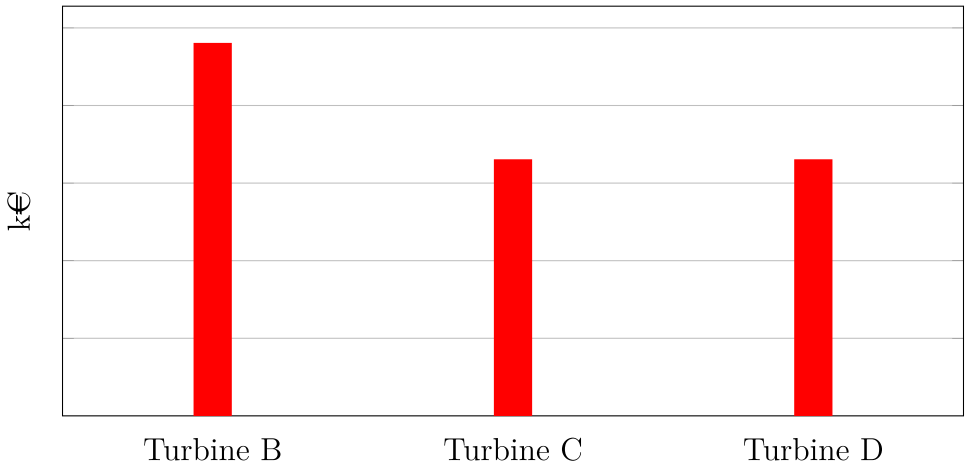


Figure 4.18: The service costs received for the different turbines

down slightly in order for the projects to be profitable with Turbine B. While the variable service cost per MWh might have seemed underwhelming at this point, it was important to remember that while for instance the turbine price was a one-time payment, the service costs would be paid each year, and per each turbine. It was deemed that the prices would need to go down somewhat, as mentioned previously, but it was also determined that a loan structure of around 65 % was not enough to secure a return on the equity used on most of the projects, and would need to be optimized for each case specifically.

Manufacturer C's offer was a lot more suitable for the project, at least after the first round of inquiries than Manufacturer B's turbine. Not only were the overall costs significantly lower (especially in terms of annual service cost), but, as the power curves suggested and the WindPRO data confirmed, the Annual Energy Production (AEP) of Turbine C was also slightly higher. The service cost for Turbine C presented in Table 4.18 was a simplified one, since actually the service cost was divided into several different stages, presented in Table 4.19 below.

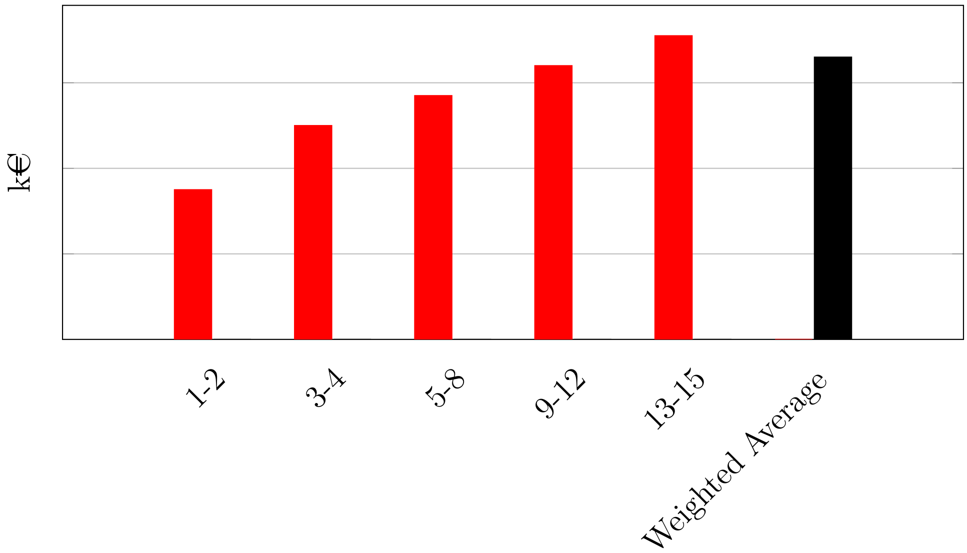


Figure 4.19: The service costs for Turbine C per year

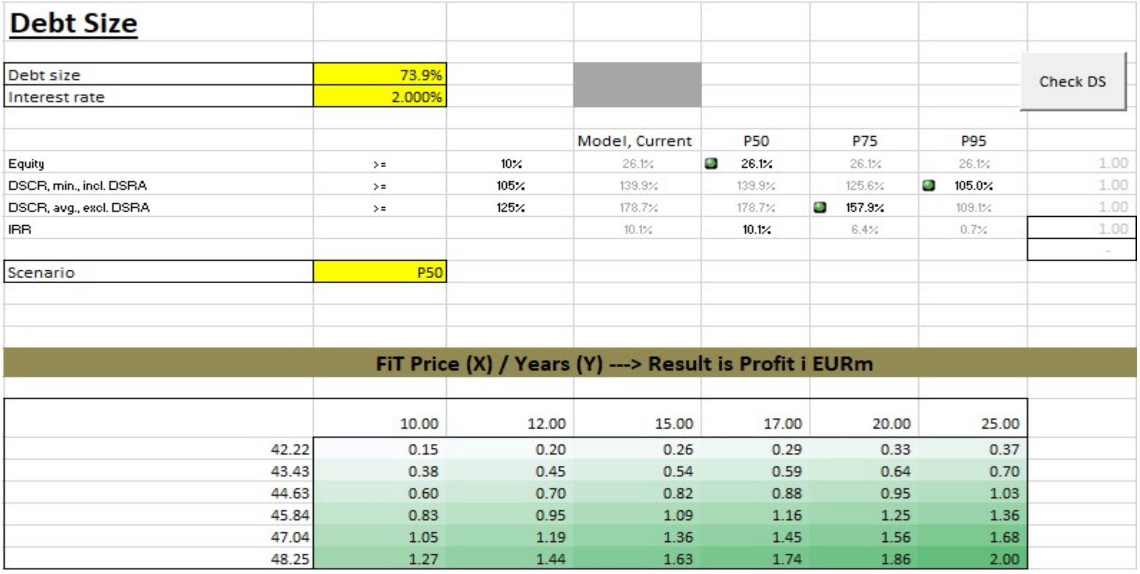
Manufacturer D's offer was, as were the others, inserted into the Excel sheet to acquire the corresponding figures for Turbine D. Manufacturer D's turbine price was dependent on the rated power of the turbine.

The amount of loan was hence subsequently under consideration, after the arbitrary choice of around 65 %. In order to increase the Enterprise value presented in the Sensitivity sheet of the Excel used, the amount of loan would need to be increased, as shown in Equation 2.7 and explained in Chapter 3. This would serve as a baseline for the suggestions for the auction bid. The goal was to find a loan structure that had a positive value for the EV with all the three different scenarios mentioned earlier:

1. 32.8 €/MWh in 2019, with a 2 % annual increase in prices
2. 25.8 €/MWh in 2019, with a 1.85 % annual increase in prices
3. 32.6 €/MWh in 2017, with a 0.036 % annual increase in prices

For this purpose, an additional Excel sheet was constructed (or rather, the Sensitivity sheet was improved to include more information): both a table of profits with different PPA or tariff schemes as well as a checklist for the different loan structures. A part of the newly constructed Excel sheet is presented below in Figure 4.20.

There were several different constraints on the amount of loan for the project that came from financing, and the obstacles needed to be overcome in order for banks to be interested in funding the projects (such as that the amount of loan cannot



Debt Size

Debt size	73.9%						Check DS
Interest rate	2.000%						
			Model, Current	P50	P75	P95	
Equity	>=	10%	26.1%	26.1%	26.1%	26.1%	1.00
DSCR, min., incl. DSRA	>=	105%	139.9%	139.9%	125.6%	105.0%	1.00
DSCR, avg., excl. DSRA	>=	125%	178.7%	178.7%	157.9%	109.1%	1.00
IRR			10.1%	10.1%	6.4%	0.7%	1.00
							-
Scenario	P50						

FiT Price (X) / Years (Y) ---> Result is Profit i EURm

	10.00	12.00	15.00	17.00	20.00	25.00
42.22	0.15	0.20	0.26	0.29	0.33	0.37
43.43	0.38	0.45	0.54	0.59	0.64	0.70
44.63	0.60	0.70	0.82	0.88	0.95	1.03
45.84	0.83	0.95	1.09	1.16	1.25	1.36
47.04	1.05	1.19	1.36	1.45	1.56	1.68
48.25	1.27	1.44	1.63	1.74	1.86	2.00

Figure 4.20: Optimizing the amount of loan for the projects, with Turbine D and Scenario 3

exceed 90 %). The constraints were also presented in Figure 4.20, and the loan (and, by extension, equity) structure was then optimized in a way that fulfills all the requirements for the different exceedance probabilities, explained earlier. This would be a key tool for investors and banks in when they evaluate whether the projects are worth investing in.

The loan structure was subsequently increased to around 75 % (each case would have its own specific value), where it was found that the returns for the projects were more in the liking of European Energy. Naturally this also meant that a lot of the figures presented earlier that were for a smaller share of loan would have to be re-evaluated, such as the ones presented in the Sensitivity sheet of the Excel. A goodwill of n_{Gw} € was again the target. Reaching this goal by iterating the values was done in the Excel sheets mentioned earlier, by changing the amount of loan on the Project Information sheet in the Excel, and then checking the subsequent Enterprise value, as well as Return on equity on the Sensitivity and ConsolidationFI sheets of the Excel, respectively.

Another important thing to mention was the baseline for the tariff or the PPA, as P_{price} €/MWh for n years was chosen as a baseline after some sensitivity testing in the Excel files.

It should be noted here that several constraints on the size of the loan existed. The amount of loan, as mentioned previously, could not exceed 90 %, and several other constraints exist due to the strict requirements of banks in order to secure their returns (In terms of DSCR and DSRA). Figure 4.20 represents some of those constraints, and an illustrative picture of the optimization process is presented in Figure 4.21 below.

The part of the Excel sheet presented in Figure 4.21 went through different wind

Table 4.5: A table showing different loan structures for the turbines with different scenarios

	Debt, SC 1	Debt, SC 2	Debt, SC 3
Manufacturer B (%)	64.3	64.3	64.3
Manufacturer C (%)	72.7	72.7	72.7
Manufacturer D (%)	73.9	73.9	73.9

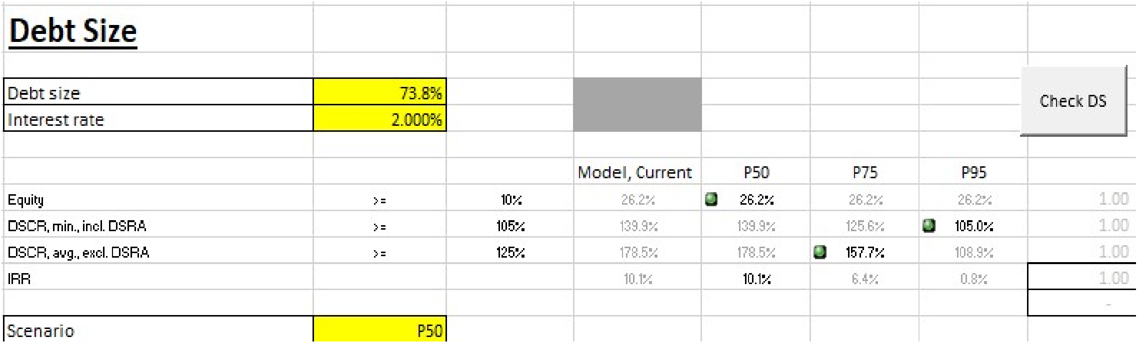


Figure 4.21: Constraints on the loan structure of the project

exceedance probabilities (the P50, P75 and P90) and ensured that the constraints set by the financial department were all met and the loan structure was viable these constraints were an equity of no less than 10 % as mentioned, as well as a minimum DSCR of 105 % while including DSRA and an average DSCR of 125 % while excluding DSRA. It also, once again, allowed easy manipulation of the figures in order to find the optimal values. The meaning of these constraints was not significant, but rather they worked to provide a framework within which the loan and the cost structure had to be optimized.

Table 4.6: A table showing the enterprise values of the projects with the respective scenarios and turbines, with per unit numbers in relation to goodwill

	EV, Scenario 1	EV, Scenario 2	EV, Scenario 3
Manufacturer B	14.1	13.5	13.2
Manufacturer C	15.7	15.0	14.8
Manufacturer D	13.4	12.8	12.6

As is apparent from Tables 4.5, 4.6 and, 4.7, large differences existed between the two best offers (A baseline support scheme of 15 years was used to acquire these figures). Turbine C had higher production (deemed in Chapter 4.3.1 as the 3rd most

Table 4.7: A table showing the profits of the projects with the respective scenarios and turbines, with the results as a percentage of the target goodwill

	Profit, SC 1	Profit, SC 2	Profit, SC 3
`Manufacturer B`	-34 %	-98 %	-120 %
`Manufacturer C`	157 %	91 %	68 %
`Manufacturer D`	172 %	113 %	93 %

important parameter), lower price (2nd most important parameter) as well as lower service costs (7th most important parameter) than that of Turbine B. On the other hand, the 2nd most important parameter, WTG prices, was heavily on the side of Turbine D.

It should also be noted here that the service costs' durations were not for the intended lifetimes of the projects, but rather an arbitrary choice by the manufacturer and somewhat of an industry standard. If the service cost offer was less than the intended lifetime of the projects, the rest of the service costs had to be estimated, which might naturally lead to unwelcome suprises. Therefore, it was deemed preferable to make service contracts for the whole lifetime of the projects or at least clear guidelines on how to proceed with maintaining the turbines after a service period of 15 years.

Two turbines stood out clearly at this stage, and thus Manufacturer B's turbine was deemed unoptimal for these projects. Turbines C and D were still in the game, with C's strength being high overall production as presented in Figure 4.12 and D's strength being costs that were significantly lower than that of the others, as presented in Figure 4.17. The choice was, however, not as simple as trying to make C decrease their costs and D increase their production. As presented in Chapter 4.3.1, WTG price as a parameter was more important than WPP production, although not by a large margin. This meant that the project could, in theory, be made to work with either Turbine C or Turbine D, but the bottom line was what matters: goodwill.

As presented in Table 4.7, even the worst-case scenario used here, Scenario 3, which was deemed somewhat unlikely as a future trend in electricity prices, reached a figure very close to the required goodwill of n_{Gw}: over 93 %. As mentioned before, the most likely development in electricity prices would likely land somewhere between the different predictions and their corresponding scenarios. Due to this, Manufacturer D's offer was deemed, with the current knowledge of the projects, as the most suitable choice for the turbine manufacturer, and the bid was therefore optimized using Turbine D, and once again, the Sensitivity sheet of the Excel files. Scenario 3 was used as a baseline, since the predicitons of Scenario 3 were the most pessimistic in terms of generated profits. It was also good to recall at this stage that the scenarios were not intended to be perfect predictions of the future of electricity markets in Finland, but rather to cover different price forecasts as a whole and the likely market behaviour would be somewhere between the different predictions or scenarios. This knowledge was then applied to all the different scenarios. The target goodwill of

n_{Gw} was nearly reached with Manufacturer D's offer, so only the largest parameters identified in Chapter 4.3.1 would be (ideally) tweaked a little in order to achieve the profit margin required. This meant that, while an integral part of wind power projects in general, for instance the grid conncetion and foundation costs presented in Chapter 4.1.2 would not be optimized at this stage as, as presented, their impact would be significantly less than for instance the impcact of turbine prices.

A part of the optimzation is presented in Figure 4.22 below.

Enterprise Value / Profit

Enterprise Value	1265%
Total Profit on Shares	17%
Profit via PMA fee	100%
CoF until financial close	-24%
Total profit befor tax	**94%**

FiT Price (X) / Years (Y) ---> Result is Profit i EURm

	10.00	12.00	15.00	17.00	20.00	25.00	**(duration)**
42.22	0.15	0.20	0.26	0.29	0.33	0.37	
43.43	0.38	0.45	0.54	0.59	0.64	0.70	
44.63	0.60	0.70	0.82	0.88	0.95	1.03	
45.84	0.83	0.95	1.09	1.16	1.25	1.36	
47.04	1.05	1.19	1.36	1.45	1.56	1.68	
48.25	1.27	1.44	1.63	1.74	1.86	2.00	
(size)							

Figure 4.22: Finalizing the auction bid both in terms of the price and duration

Figure 4.22 presents the final stage of the bid optimization, and finalizing the bid both in terms of size P_{price} and the duration n: the suitable combinations (per unit numbers used here) were marked in black. This was done for all the different scenarios, although Scenario 3 was used here to represent all of them, since a combination of P_{price} and n that yielded a high enough profit in Scenario 3 would work with all of the scenarios. It was important to note here that Figure 4.22 only represents one loan structure, and changing the PPA agreement changes the enterprise value, which in turn affects the loan structure and its constraints presented earlier. Therefore the figures presented above are only accurate when looking at durations over 15 years, since the figure was the result of a 15 year PPA/support scheme iteration. This was done for each case specifically, and the results are presented fully in Chapter 5.

Due to the nature of the auction, different recommendations for the auction were made, both for longer and shorter terms. This was done regardless of the fact that the initial draft of the new renewable energy auction scheme would indicate the new support scheme period to be for 12 years, as presented in little more detail later. The option lasting 12 years was highlighted, however, since that was regardless deemed as the most likely outcome.

An important addition here was that, due to the nature of the auction scheme, it was important to keep the bid as competitive as possible. Due to this, figures very close to the target goodwill of n_{Gw} were accepted. This was partly to keep the bid as competitive as possible, and partly for a more practical reason: in a long process such as the process of building a wind power plant, a lot of figures have to be estimated. Due to the inaccurate nature of some of the figures (or even the ones perveived as being more accurate being preliminary), it was pointless to think of the results as completely accurate, and some small deviations were allowed. The auction bid is presented in Chapter 5. Naturally, as the negotiations would proceed with the turbine manufacturer, the most important components (that they can influence) such as WTG price, would ideally be lowered slightly in order to reach the target profit. This would, according to the calculations, require a decrease in the prices of around 1 %, which was deemed reasonable.

After first presenting the offers, then inserting the values into the Excel sheet, followed by a sensitivity analysis and then optimizing the most crucial parts of the wind power plant development process (or the ones that could be optimized), the thesis now moves on to presenting the offer in its entirety.

5 Results

The results obtained for optimizing the cost efficiency of wind power plants are presented here.

5.1 Analysis of the Results

The aim of this master's thesis was to look at several different turbine manufacturers and then determine the most suitable one for the projects under consideration. This would then be preceded by utilizing the data acquired for the turbine and optimize the cost structure of the projects in preparation for the bid at the auctions to be held later in 2018, while simultaneously building a comprehensive understanding of the most important aspects of the cost structure and the cost of energy of a wind power plant, and how these aspects could be optimized.

5.1.1 Components to Optimize When Looking at the Cost of Energy of Wind Power Projects

As identified in Chapter 2 and after reinforcing that notion in Chapter 4.3.1, the cost structure of WPPs was dependent on many different things. The production, losses and cost of the turbines, in terms of pure cost, base service cost per year as well as a production variable service cost fee were found to be important factors in the cost components of a wind power plant project. Power purchase agreements or other support schemes also play a huge role in the cost structure of a wind power plant, and especially the size of the FiT or PPA can make or break a project. The foundation of the turbine and by extension, road requirements and weight, are also an important factor when optimizing costs in a wind power project. Turbine weight also comes into play with the height of the turbines: it was deemed that some sites might need site-specific tailored tower solutions, and in order to keep the costs as low and possible, a lot of turbines would need to be grouped together in cases where the tip height restriction of the turbines set by the site does not match that of the existing turbine models. Grid connection needs to be ensured beforehand, so that it does not impose additional costs to the projects. Land rent and financial costs can also play a small part in the cost structure, as can consultancy and control system costs. Naturally, background knowledge of the sites can be of vital importance when looking at things such as land rent, balance and consultancy costs, and better information can lead to decreased costs. Several indexes, such as interest of the debt used to finance the project as well as predictions about future electricity prices also have an impact on the cost structure of a wind power plant. The thesis pointed out, with the use of different scenarios, the importance of having a good prediction not only for the current price of electricity, but also the vital importance of the future developments of energy or electricity prices, whether one chooses to enter into a power purchase agreement or a tariff system or not. This would serve in not optimizing the cost structure of the power plants in question by not reducing costs, but rather increasing profits.

The result of this master's thesis in terms of identifying the most crucial economic components confirmed some of the earlier research on the subject. The components identified in Chapter 2 were confirmed to be among the most crucial components in designing wind power plants (but they were not the only ones), and improvements to the list were made when looking at the whole process of a wind power plant project: the importance of support schemes or power purchase agreements were highlighted, things such as balance costs, grid usage fees and development fees were added, the list was made more specific with the inclusion of paying extra attention to the service costs and the losses of a turbine, since small differences in the service costs of a large project can have a relatively big impact on the outcome when optimizing the cost structure, and it was pointed out that the production of the turbine, assumptions about electricity price indexation as well as the power purchase agreement or tariff scheme are also of great importance. Similarly, the list was made more complete by adding things such as land lease agreements and including the interest rate of the debt that the project is financed with. It was noticed that a total service cost would often be preferable to a version with both a varying service cost and a base service cost, as the variable costs can lead to the whole service cost being too high. Additionally, it was pointed out that a service agreement covering the whole lifetime of the project would be beneficial, as service agreements might often be for only a portion of the intended lifetime of a project, such as a 15 year service agreement for a project with a lifetime of 25 years.

5.1.2 Recommendations for the Auction Bid Based on the Data and the Initial Proposal

Chapter 4.3.1 and the initial WindPRO data was used to determine that the most suitable turbine for the projects in terms of production was Manufacturer C's offer, with the highest annual energy production. The Sens sheet in the Excel file was then used to determine an acceptable price range for the different turbines. As mentioned before, entering all the required data in the ConsolidationFI sheet on the Excel allowed the calculation of the COE of the projects. Auction bids are often just offers to produce energy at a certain price per MWh, and the ConsolidationFI sheet allowed the calculation of the cost of energy, in €/MWh, to be used in the bid.

After acquiring the first round of the offers for the actual turbines and their service costs and very rapidly ruling out Turbine A, Turbine C looked even more tempting as a choice, due to the fact that the price range was similar to that of Turbine B, but with a production rate that was a bit higher. Turbine D could not compete with the other two turbine types in terms of production, but with a price per turbine significantly less than that of the others, freshly identified as one of the main cost components of a wind power plant project, it was also an attractive offer at that stage. After constructing a table of the profits of the different turbine types, it became clear that although Manufacturer D's offer was somewhat lacking in production, its superior price range made it the best fit for these projects. Therefore, Turbine D was chosen as the best choice for the projects.

Rather than a simple solution which would cut many corners in a case with exceedingly many variables, the thesis provides a few recommendations to the different projects and scenarios. Different combinations of pricing forecasts result in different enterprise values, which affect both the debt structure possibilities and the profits of the project. Again it should be noted that there were a few conditions that would have to be met for the projects to be attractive investments: a goodwill of n_{Gw} as well as various other constraints put on the project by the financing department, which were beyond the scope of this master's thesis.

An initial draft or proposal of the support scheme for renewable energy in Finland was released shortly before the completion of this master's thesis. The draft was largely as expected, with some of the details that have an impact on this thesis being as follows: [42]

- A technology-neutral (not just wind power is accepted, but rather a range of different renewable energy generation techniques could apply) renewable energy auction system, in which bids are made to produce electricity at a certain premium fee price point, with a quota of 2 TWh
- A Feed-in premium system, with the referene price being 30 €/MWh and the bids would be offers to generate electricity with different price points in regards to the reference price. This meant that if a bid of 30 €/MWh was victorious and accepted into the 2 TWh, the price received by the electricity producer would be 60 €/MWh when market prices are above the reference price, and a maximum premium of 30 €/MWh if market prices are below the reference price: if the price went down to 25 €/MWh, the maximum premium that the producer would receive would be 30 €/MWh and therefore a total of 30 €/MWh + 25 €/MWh = 55 €/MWh
- The premium duration would be for 12 years
- The auctions would be held in 2018 and 2019
- Possibly a limitation of 10 000 MWh per turbine

It was decided, with the support of Scenarios 1, 2 and 3, that while a future electricity price point of less than 30 €/MWh and therefore a smaller total income was possible, it was unlikely enough to not warrant great action at this stage of the thesis, and that the proposal would be done as normal. This supported the notion that the thesis used FiT and FiP interchangeably, since from the point of the electricity producer, if electricity price does not go below the reference price, a feed-in premium and a feed-in tariff system are similar. Although Scenario 2 does present a scenario where market price would go below the reference price, leading to a smaller income, Scenario 2 also depicts a strong rise in electricity prices subsequent to the temporary dip below reference price, and therefore Scenario 3 was still deemed as the scenario to test and calculate with. Additionally, projects can be insured against prices dropping too low, and this would be done if it seemed likely that the market price would drop far below the reference price.

The most challenging limitation in regards to these projects might be the limit of 10 000 MWh per turbine, but this could easily be counteracted by changing the turbine type to one with a smaller rated power, so that it would produce less.

Based on all of the information provided, the auction bid would be as presented in Table 5.1. As mentioned before, the bid would be a collection of recommendations, made on a worst-case scenario basis, and, while a preliminary decision could be made with the available information, the final decision would be made closer to the actual auction, to be held later in 2018. The options presented in Table 5.1 did, however, all meet the important criteria of a profit or goodwill target of $\mathbf{n_{Gw}}$ and a return on equity of $\mathbf{n_{RoE}}$. The bolded part would be the likely bid, as it was deemed likely that the initial draft of the renewable energy support scheme as a feed-in premiums system and its duration of 12 years would hold.

Table 5.1: A table showing the profits of the projects with the respective scenarios and turbines, with the results as a percentage of the target goodwill, as well as the likely bid based on an early draft of the renewable energy auction system to be implemented in Finland

Duration	Size	Debt	Turbine
10	50.3	60.3 %	D
12	***49.2***	***60.3 %***	***D***
15	45.1	73.9 %	D
20	44.8	73.1 %	D

Looking at Table 5.1 it could be for instance said that if a shorter PPA or support scheme was preferred, the company could undertake projects with a 10 year power purchase agreement of 50.3. On the other hand, if a smaller size was preferred by either the government or the company, an agreement for 20 years could be made with a price point of 44.8.

The bid for the auction based on the preliminary information about the auction would then, as according to Table 5.1, be 49.2 in total, with the reference price of 30 €/MWh subtracted from the final premium price as well as a debt size of 60.3 %:

Table 5.2: A table presenting the probable bid for the renewable energy auction in Finland

Premium Price	Profit	Debt	Turbine
49.2 -30 €/MWh	0.92	60.3 %	D

As a sidenote, it was also noticed that the following also fulfilled the criteria of $\mathbf{n_{Gw}}$ and $\mathbf{n_{RoE}}$:

Table 5.3: A table presenting the best-case scenario, but without a support scheme, in Finland, for 12 years

Scenario	PPA/FiT scheme	Debt	Turbine	Profit
1	No	65.7 %	D	1.15

In other words, as presented in Table 5.3, WPP projects would already be at grid parity in Finland if prices rose at a steady rate of 2 % annually (at the rate of inflation!) and had a starting point of around 31.5 €/MWh in 2017.

After Chapter 5 explained and analyzed the results as well as presenting the actual product chosen by this master's thesis the thesis now moves on to summarizing the key points of the thesis.

6 Summary

This Master's thesis studied the cost optimization of wind power plants through both a literature research, as well as a practical one with software simulations and calculations. The aim was to gain a clear and comprehensive understanding of the main components that contribute to the cost of a wind power plant, and then utilize that information in order to make the best possible suggestion for the upcoming wind/renewable energy auction in Finland for European Energy to use: RoE and COE should be optimized. Actual offers from turbine manufacturers A, B, C and D were reviewed, and the technical as well as financial characteristics of those offers were considered. Only one of the projects was presented in more detail, Mustalamminmäki, as the initial calculations were made for that site in order to determine the most cost efficient solution in terms of turbine, and the knowledge was then applied to the other projects as well.

6.1 Recapitulation

After a brief introduction the thesis built a comprehensive understanding of the cost structure of wind power plant, as well as the basic functioning of a wind power plant and the knowledge surrounding it. The most fundamental equations in wind power plant design, such as the estimation of wind speeds at different heights were examined, as well as the power prodction of a WPP. The wind speed, or the cube of wind speed, was found to be an important factor in determining the output of a wind turbine: three important characteristics in terms of the production of a wind power plant were identified as the volume of air, the velocity of air as well as the mass of air. It was noticed that the turbine is not only the main cost component of a wind power plant of a certain size, but scaling up the power of the turbine increases turbine weight, which was determined as being one of the main factors that increase the cost of a wind power plant. Other main components that impact the cost structure of a wind power plant were also identified, such as grid connection and congestion, foundation and land rent. It was discerned that the costs of a wind power plant could be divided into three sections: direct, indirect and externality costs. Direct costs included, among other things, Operations & Management costs, as well as capital costs, while indirect costs covered things concerning grid connection. Externality costs, on the other hand, were identified as other effects, possibly perceived as harmful, such as visual pollution as well as noise pollution. LCOE was identified as an important metric when comparing different kinds of projects to each other, but it was also subsequently noted that an LCOE approach is not free from problems either. Important terminology surrounding wind power plants were examined, such as the capacity factor, specific power and system-friendly turbines. The profits produced by a wind power plant were found to be dependent not only on the production of the turbine or turbines, but also the price of electricity for which it is sold. Different electricity pricing schemes were examined, such as tariffs, power purchase agreements and premiums, and their impact economically (both in terms of size and duration) were examined. Important terminology and methods regarding this master's thesis were examined when looking at things such as the power curves of different WTGs, as well as looking at the equations and important financial considerations such as (by extension) NPV, IRR, Goodwill and RoE as well as their implications, including the fact that the loan used to possibly monetize these projects would also be an important factor when thinking of the bid that European Energy would do in the auction. The thesis also took a brief look at grid congestion and adding wind power to the grid as a part of the financial considerations of a wind power plant. A brief overview of the future direction of wind power plants was also considered, with suggestions to both improving profits with things like advanced control methods and minimizing costs such as moving to cheaper and lighter equipment, decreasing the weight and subsequently the costs of a wind power project.

Then the thesis moved on to presenting both the material and the methods used during the completion of the thesis. Materials included both well-established literary works in the industry, as well as more detailed scientific studies about certain aspects of the wind energy production process, as well as comprehensive outlooks and summaries of wind power projects around the world by international organizations. Methods were divided into the two main methods that were used in the completion of this master's thesis: the WindPRO software and, most importantly, Microsoft Excel. The use of the WindPRO software was briefly explained, including things such as inserting coordinates for the turbines in WindPRO, as well as geographical data that might affect the free flow of gusts of wind in the area. The different WindPRO modules were not explained in detail, but the results of the PARK module were divided into several sections and represented visually as well as with a few words, such as the main result, as well as the production analysis, the wind data analysis and the WTG distances section. These were used to illustrate the detailed data that could be acquired using the WindPRO software, and which was done in order to complete this master's thesis and acquire detailed data for the Excel analysis. Some of the WindPRO data was analyzed or explained, such as the Weibull distribution and the energy rose of a specific wind power plant project. After briefly explaining the WindPRO software in the Materials chapter, the thesis then moved on to looking at the other, more significant, part of the materials chapter: the Excel analysis. The contents of the Excel sheet that was the main tool used in the completion of this master's thesis, were explained with an illustrative example. The Excel sheet was explained to have been divided into several sections, all of which were integral to the successful completion of this thesis. These sections included things like Project Information, which holds a lot of the basic data of the projects such as the annual yield of the turbines as well as the size and duration of the tariff, information about capital costs and financing. Another section that was explained was the main "result" sheet of the Excel and the thesis, with ConsolidationFI including detailed breakdowns of the costs and profit of the projects as well as important information regarding the monetization of the project and the interest of the investors: RoE and Goodwill. Base Assumptions- sheet was explained to be a brief overview and breakdown of most of the information in the Project Information sheet, in a more approachable and understandable form, showing for instance the loan structure as a percentage of the total investment. Base Financing was presented and it turned out to be exactly as the name states: a detailed breakdown of the loan structure, also touched upon in the Base Assumptions sheet. Finally, the Sensitivity (Sens) sheet was presented, which was used both in giving a rough idea of the price range European Energy would be prepared to pay as well as finalizing the cost optimization of the identified components. Sens shows the Enterprise value as well as profit margins for different combinations of turbine and service costs, which were utilized in this project package of 24 turbines and four projects. A figure showing the relations of the different sheets was also presented in order to illustrate the dependencies between the different sections.

The fourth chapter of this master's thesis marked the end of the introduction to the materials, methods and ideas surrounding this thesis and moved on to the actual cost optimization of wind power plants, as the name suggests. The first thing that the thesis looked at in this chapter was the electricity price in Finland, as well as taking a brief look at the structure of the electricity markets that Finland finds itself in. It was established that Finland usually has a deficit in its electricity production, and that electricity prices in Finland are somewhat volatile and difficult to predict. A few different methods in trying to predict the electricity price in Finland were examined, such as a forecast done by experts, as well as an arbitrary figure of 2 %, used to mimic inflation. In addition, compromises between these approaches were examined, where experts' predictions were followed with a 2 % annual increase in electricity market prices, and a model where electricity prices stayed around the same figure until the end of the lifetime of the projects in 2044, but with a slower annual increase, and different scenarios to predict future outcomes of electricity prices were constructed. It was determined that predicting electricity prices and future developments of the electricity trading market would be challenging, and other measures would need to be used in estimating the cash flows of the projects. This meant that juggling between several different scenarios was required in order to gain as broad an understanding as possible of future price developments: predicting the actual electricity prices and the annual increase of those prices was not the target, but rather to cover as much ground as possible with the different predictions, and most likely the real scenario would fall between the three differrent scenarios presented.

The first subchapter the cost optimization of wind power plant projects presented the offers from the wind turbine manufacturers. The power curves of Manufacturers A, B, C and D were presented, as well as an illustrative figure of them all in one figure, in order to highlight the differences between the turbines. Some of the most notable differences in the power curves of the turbines were presented, as well as other information regarding the different turbines. This other information included important aspects of the turbines as well, such as delivery times for the turbines, the structure of the turbine: whether it was going to be a steel or a hybrid turbine, height of the turbines and the possible need of a site-specific solution, as well as the actual cost of the turbines themselves. The thesis then moved on to presenting the WindPRO data yielded utilizing the power curves from the different manufacturers and their respective offers for the Mustalamminmäki site. The annual yields of all the four different manufacturers' turbines were presented, as well as their capacity factors and mean wind speeds at hub height, among other things. It was determined that, according to WindPRO production data, Manufacturer C's turbine rose above the others, with Manufacturer B's solution coming quite close. Turbines A and D had an annual yield of significantly less. In terms of pricing, however, Manufacturer D's turbine rose above the others quite clearly. Other costs, including costs for foundation, grid connection and road construction costs were also presented. Finally, an additional Excel analysis was completed in order to acquire a comprehensive answer to the most important questions posed by this thesis: the most crucial cost components of a wind power plant project. The Sens and Basic Financing sheets were used to gain an understanding of the initial ideas for both loan structure as well as the cost (both service and total) of the turbines. The Excel sheets presented earlier were then used, as also presented earlier, to gain a fundamental understanding of the most critical cost components of a wind power plant. The most important components in terms of the total cost of a wind power plant project were found to be FiT/PPA size, turbine prices, production of the turbines, FiT/PPA duration and total losses and power price indexation followed by less significant factors. After presenting the important details about the different manufacturers' offers as well as presenting the initial draft based on which the actual decision for the renewable energy auction was made, Manufacturer D's turbine was deemed the most suitable for the projects in Finland, and it was determined that Turbine Type D was the optimal choice. Figures such as a FiP system with a duration of 12 years and the reference price for the premium being 30 €/MWh were inserted into the calculations, and Turbine type D was then optimized in terms of debt structure with the worst-case scenario, 3, in order to attain the most competitive bid for the upcoming auction.

6.2 Conclusions

One of the first and one of the most fundamental conclusions that could be drawn from this master's thesis in terms of the COE of wind power projects was the importance of electricity prices, and the fundamental, underlying assumptions when making predictions regarding electricity prices and therefore the profits of a wind power plant (and, by extension, naturally also the estimates for wind speed and production are of great importance). Accurate estimates of current electricity prices as well as the increase in electricity prices lead to good estimates of the cost structure of wind power plants with no support scheme. The possibility of a tariff/premium or power purchase agreement system means that good estimates of the support scheme are required in order to make important decisions and determinations surrounding the cost structure optimization of wind power plants: an estimate of the electricity prices that turns out to be too low would make an otherwise unattractive tariff scheme look good, and if the estimate turns out to be too high, it could possibly lead to the company making the financially damaging decision of not getting into the support scheme when one is offered.

In terms of optimizing the COE of a wind power plant project, the results were partially as expected with the knowledge gained from Chapter 2: the turbine costs as well as the service costs for said turbines were determined to have a big impact on the financial aspects of wind power plants. An even greater impact, however, was discovered with the size of the PPA, while the duration of the PPA or the tariff system was also found to be significant. These were followed by the production of the turbines as well as the losses, the changes in power prices, service costs of the turbines, land lease costs, grid connection costs, interest of the debt used to finance the project, balance costs as well as the cost of construction and foundation. Additional components that have some impact on the price were financing costs, grid usage fees, development costs, financing fees, technical surveillance, own power consumption, handling fees, and project management fees. Additionally, it was determined that service costs might come in several parts, and an initial base service cost might become an unattractive offer when addding the variable service cost offered. As a sidenote, it was noticed that it would also be beneficial to secure agreements for the whole lifetime of a project, if possible.

An important sidenote to make when listing the crucial components of the wind power plant projects under consideration and their economic structure, was the applicability of the information. While the information provided would undoubtedly serve as a good baseline for optimizing the cost structure of wind power plants and maximizing the profits they generate, it was important to keep in mind that the baseline for the calculations was projects for European Energy. For instance, some wind power plant constructors or developers might be inclined to group together several aspects of financing, instead of keeping them more separate like the Excel template here does. In those cases, the relative importance of a bigger component is naturally larger.

Another important thing to note regarding the cost components of a wind power plant was the fact that the most crucial component in the economic structure of a wind power plant project turned out to be the size of the support scheme or purchase agreement. This was definitely a key observation to keep in mind regarding future wind or renewable energy projects, as support schemes or purchase agreements in many markets might be on the decline or they are being reconsidered. However, the most sensitive components identified after FiT/PPA size were the prices of the turbines themselves, as well as their production. If price developments continue to go down while production goes up, wind power is still heading in the right direction. However, this was, at least for the time being, not the case in Finland, as the new renewable energy auction system to be held in 2018 and 2019 would be a feed-in premium based system lasting 12 years, paid on top of the market price, with regards to the market price.

After deciding that Manufacturer D's offer was the most suitable for the projects at hand with the current information available (and that if the new support scheme does things such as limit the maximum size of a turbine to 10 000 MWh, it was easy to change), the upcoming bid was optimized as far as possible. A small margin of difference in terms of the required goodwill, n_{Gw}, was ignored in favour of the most optimal bid. This was done due to the fact that the auction would likely be very competitive, and it was important to ensure that the bid would be as competitive as possible. Another reason for this was the fact that some of the information was preliminary, and it was deemed likely that some facts and figures might change, and that further optimization would be unnecessary at this stage. It was pointed out, however, that with a mere 1 % decrease in turbine prices the profit targets would likely be reached even with the worst-case scenario, Scenario 3, which was used to optimize the bid.

It was ultimately decided that not only are the renewable energy auctions in Finland worth participating in, but it could be done with competitive prices. While grid parity was not reached and one might be inclined to think that renewable energy projects, such as wind power projects, are completely dependent on a support scheme, this thesis does not necessarily support that image. agreements or support schemes, such as feed- in tariffs or premiums can be exploited in certain markets to a great extent, but they also work as a buffer for investors and developers against somewhat volatile and unpredictable electricity prices, and can make locations such as Finland, with average wind resources, an attractive place to construct renewable energy. (As a sidenote, it should be noted that often tariffs or premiums are not adjusted according to inflation, making the support schemes less and less impactful over time.) As presented, a feed-in premium system was also chosen in Finland as the way forward, which would guarantee a certain premium for electricity producers, but would also shield the government from paying excess subsidies. As proved with Scenario 1 and Turbine D, grid parity is indeed on the horizon even in markets such as the Finnish one, and reaching grid parity is not a question of if, but when. As argued in the beginning of this thesis, renewable energy is the way going forward. Supporting renewable energy is supporting the future.

References

[1] The European Union. EU Climate Action: 2050 Low-Carbon Economy 2016. Online article, accessed 07.06.2017. *EU.* Available at: https://ec.europa.eu/clima/policies/strategies/2050_en

[2] The United Nations Framework Convention on Climate Change. Paris Agreement- Status of Ratification. 2017. Online article, accessed 07.06.2017. *United Nations.* Available at: http://unfccc.int/paris_agreement/items/9444.php

[3] The International Energy Agency. World Energy Outlook 2014. *IEA*. 2014.

[4] The International Energy Agency. About Wind Energy. 2016. Online document, accessed 30.5.2017. *IEA*. Available at:https://www.iea.org/topics/renewables/subtopics/wind/

[5] Global Wind Energy Council (GWEC). Outlook, Global Wind Energy. *GWEC.* 2006.

[6] Global Wind Energy Council. Global Statistics, Wind Energy. 2016. *GWEC* Online article, accessed 07.06.2017. Available at: http://www.gwec.net/global-figures/graphs/

[7] European Wind Energy Association. The Economics of Wind Energy. *EWEA.* 2009.

[8] The Official Website of the Government of Denmark. A World-Leader in Wind Energy. 2015. Online document, accessed 06.06.2017. *The Government of Denmark.* Available at: http://denmark.dk/en/green-living/wind-energy/

[9] European Energy. European Energy's Home Page. 2017. Online article, accessed 03.07.2017. *European Energy.* Available at: http://europeanenergy.dk/en/home/

[10] Landberg, L. Meteorology for Wind Energy. *John Wiley & Sons Inc.* 2016.

[11] Hau, E. Wind Resources. *Wind Turbines. Berlin, Heidelberg: Springer, Chap. 13.* 2014.

[12] World Meteorological Organization. Guide to Meteorological Instruments and Methods of Observation. *WMO-No.8, 7th Edition.* 2008.

[13] Zhang, X. Optimal Wind Bidding Strategy Considering Imbalance Cost and Allowed Imbalance Band. *IEEE.* 2012.

[14] Wizelius, T. Developing Wind Power Projects: Theory and Practice. *Earth-Scan.* 2007.

[15] Valentine, S. Understanding the Variability of Wind Power Costs. *Renewable and Sustainable Energy Reviews 15.* 2011.

[16] Lacal-Arántegui, R. Serrano-González, J. JRC Wind Status Report. 2015. Online article, accessed 08.06.2017. *Joint Research Centre of the European Commission.* Available at: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/2014-jrc-wind-status-report?search

[17] van Kooten, G. All You Want to Know About the Economics of Wind Power. *University of Victoria, Department of Economics: Resource Economics & Policy Analysis Research Group.* 2015.

[18] Kalmikov, A. Dykes, K. Aurajo, K. Wind Power Fundamentals. 2010. Online document, accessed 07.06.2017. *MIT.* Available at: http://web.mit.edu/windenergy/windweek/Presentations/Wind%20Energy%20101.pdf

[19] Blanco, M.I. The Economics of Wind Energy. *Renewable and Sustainable Energy Reviews 13.* 2009.

[20] Nordpool. Nordpool Elspot prices. 2017. Online article, accessed 23.06.2017. *Norpool website.* Available at: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/FI/Monthly/?dd=FI&view=table

[21] Suomen konepäällystöliitto. Voima & Käyttö . 2016. Online document, accessed 23.06.2017. *Suomen Konepäällystöliitto 10/2016.* Available at: https://www.ael.fi/sites/default/files/pdfs/voimakaytto-10-2016.pdf

[22] Narbel, P.A. Hansen, J.P. Lien, J.R. Energy Technologies and Economics. *Springer International Publishing.* 2014.

[23] May, N. The Impact of Wind Power Support Schemes on Technology Choices. *Energy Economics.* 2017.

[24] Betz, A. Introduction to the Theory of Flow Machines. *Oxford: Pergamon Press.* 1966.

[25] Demarzo, P. Berk, J. Corporate Finance, 3rd edition. *Pearson.* 2011.

[26] Feldman, S. A Primer on Calculating Goodwill Impairment: Valuation Issues Raised By Financial Accounting Statement 142. *Axiom Valuation Solutions.* 2004.

[27] Klug, H. What does Exceedance Probabilities P90-P75-P50 Mean? *DEWI Magazin Nr. 20, Februar 2006.* 2006.

[28] Huang, Y. Wang, D. Shang, L. Zhu, G. Tang, H. Li, Y. Modeling and Stability Analysis of DC-Link Voltage Control in Multi VSCs with Integrated to Weak Grid. *2017 IEEE Transactions on Energy Conversion.* 2016.

[29] Clausen, N-E. Mortensen, N. Hansen, K. Cronin, T. Morthorst, P. Jensen, L. Planning and Development of Wind Farms, Handouts for DTU course 45700. *Risø National Laboratory for Sustainable Energy.* 2009.

[30] Amada, J. Moreno, P. Reactive Power Injection Strategies For Wind Energy Regarding Its Statistical Nature. *IEEE.* 2006.

[31] Elovaara, J. Haarla, L. Sähköverkot 1: Järjestelmätekniikka ja sähköverkon laskenta. *Otatieto* 2011.

[32] American Wind Energy Association. The Cost of Wind Energy in the U.S. 2017. Online document, accessed 13.06.2017. *AWEA.* Available at: http://www.awea.org/falling-wind-energy-costs

[33] Firestone, J. Kempton, W. Public Opinion About Large Offshore Wind Power: Underlying Factors. *Energy Policy 2007.* 2007.

[34] United Nations. Kyoto Protocol to the United Nations Framework Convention on Climate Change. *UNFCC.* 1988.

[35] The European Offshore Wind Association. The European Offshore Wind Industry- Key Trends and Statistics 2016. 2017. Online article, accessed 07.06.2017. *EWEA.* Available at: https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-and-statistics-2016/

[36] The International Energy Agency. Technology Roadmap, Wind Energy, 2013 edition 2013. Online document, accessed 18.07.2017. *IEA.* Available at: http://www.iea.org/publications/freepublications/publication/Wind_2013_Roadmap.pdf

[37] WindPRO A/S. About WindPRO and Modules. 2017. Online article, accessed 07.06.2017. *WindPRO.* Available at: https://www.emd.dk/windpro/windpro-modules/

[38] Kanellopoulos, D. Wind Measurement Lidar-Sodar. 2016. Online document, accessed 26.06.2017. *EU-GCC Clean Energy Network II.* Available at: http://www.eugcc-cleanergy.net/sites/default/files/events/Oman2016/S4%20Oman%20Wind%20energy_Lidar%20Sodar%202016.pdf

[39] Fingrid. Energy Production in Finland 2017. Online article, accessed 30.06.2017. *Fingrid.* Available at: http://www.fingrid.fi/EN/ELECTRICITY-MARKET/LOAD-AND-GENERATION/Pages/default.aspx

[40] Pöyry. EU:n 2030 ilmasto- ja energiapolitiikan linjausten toteutusvaihtoehdot ja Suomen omien energia- ja ilmastotavoitteiden toteutuminen. *Valtioneuvoston selvitys- ja tutkimustoiminta.* 2016.

[41] Svensson, H. Design of Foundations for Wind Tubines. *Lund University.* 2010.

[42] Työ- ja elinkeinoministeriö. Luonnos hallituksen esitykseksi laeiksi uusiutuvilla energialähteillä tuotetun sähkön tuotantotuesta annetun lain ja tuulivoiman kompensaatioialueista annetun lain 6 §:n muuttamisesta. 2017. Online document, accessed 19.09.2017. *TEM.* Available at: http://tem.fi/documents/1410877/2132292/HE_luonnos+14092017.pdf/5c7f255e-1568-4298-8672-6dc7927dcdc1